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GENERAL DESIGN STUDY
OF
PILOT VOC CONTROL UNITS

by

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Knoxville, Tennessee 37923

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The Industrial Environmental Research Laboratory (IERL), in support of the Office of Air Quality Planning and Standards Volatile Organic Compounds (VOC) Program, has established a project for design, construction and operation of four pilot emission control units which will be transportable and represent state-of-the-art technology. The control technologies represented in the pilot systems will be (1) carbon adsorption with regeneration, (2) thermal incineration with heat recovery, (3) catalytic incineration with heat recovery, and (4) condensation. It is anticipated that the four systems will be used on actual VOC emissions from industrial processes for definition of control VOC emissions from industrial processes for definition of control feasibility, efficiencies, and to provide data for system scale-up.

Since existing designs for small adsorption or incineration systems are not flexible enough to meet the needs of these applications, the pilot systems will be designed to meet the specifications outlined in this report. The designs for these pilot systems include provisions for collecting all of the data necessary to evaluate the performance of the system and to provide a sound design basis for a full-scale system.

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

The study defined, on a preliminary basis, the technical requirements and estimated costs for engineering design and construction of four pilot-scale volatile organic compound control units. This information is to be the basis for consturction of a pilot-scale unit. It is anticipated that the unit will be used on actual emissions from industrial processes for definition of control feasibility, efficiencies, and to provide data for system scale-up.

For further information concerning this subject, the Industrial Pollution Control Division should be contacted.

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ABSTRACT

The Industrial Environmental Research Laboratory (IERL), in support of the Office of Air Quality Planning and Standards Volatile Organic Compounds (VOC) Program, has established a project for design, construction and operation of four pilot emission control units which will be transportable and represent state-of-the-art technology. The control technologies represented in the pilot systems will be (1) carbon adsorption with regeneration, (2) thermal incineration with heat recovery, (3) catalytic incineration with heat recovery, and (4) condensation. It is anticipated that the four systems will be used on actual VOC emissions from industrial processes for definition of control feasibility, efficiencies, and to provide data for system scale-up.

Portable, pilot emission control units should be constructed for the carbon adsorption, thermal oxidation and catalyzed thermal oxidation technologies. A pilot condenser should not be assembled because condensers are limited in their ability to achieve low outlet concentrations and because the principles for designing a full-scale condenser have been studied extensively in the past.

Since existing designs for small adsoprtion or incineration systems will not be flexible enough to meet the needs of these applications, the pilot systems should be designed to meet the specifications outlined in this report. The designs for these pilot systems should include provisions for collecting all of the data necessary to evaluate the performance of the system and to provide a sound design basis for a full-scale system.

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I. INTRODUCTION

The Industrial Environmental Research Laboratory (IERL), in support of the Office of Air Quality Planning and Standards Volatile Organic Compounds (VOC) Program, has established a project for design, construction and operation of four pilot emission control units which will be transportable and represent state-of-the-art technology. The control technologies represented in the pilot systems will be (1) carbon adsorption with regeneration, (2) thermal incineration with heat recovery, (3) catalytic incineration with heat recovery, and (4) condensation. It is anticipated that the four systems will be used on actual VOC emissions from industrial processes for definition of control feasibility, efficiencies, and to provide data for system scale-up.

The purpose of the work under this directive is to define, on a preliminary basis, technical requirements and estimated costs for engineering design and construction of the four control units. The major work tasks for this directive will include: establishing baseline criteria for the pilot plant system design, preliminary process design and equipment description, and cost estimating.

Since this report deals with four different technologies, the report is organized so that each technology is considered in a separate section. Each section contains a general discussion of the technology, conclusions and recommendations for the design of the pilot plant and a discussion of the pilot plant design basis.

II. CARBON ADSORPTION PILOT UNIT

A. GENERAL

Vapor-phase carbon adsorption is a versatile and valuable air pollution control technology because it is usually the only nondestructive technique that can effectively and economically remove volatile organic compounds (VOC) from atmospheric emissions when the exhaust concentrations are below 5,000—10,000 ppm. Even though more than 725 adsorption systems have been installed in numerous industries to achieve improved solvent recovery and/or emission control, very little performance data (especially with respect to the ability to achieve low outlet concentrations) are available.(1) Process parameters, for which very little data exist, include working adsorption capacity, carbon lifetime, effect of steam consumption on the adsorption capacity and effluent concentration, and the effect of different relative humidities on adsorption capacity and effluent concentration. These process parameters are listed and discussed in Part D-4 and elsewhere. These data gaps exist because the majority of the existing full-scale systems were installed to achieve improved solvent recovery but not necessarily to achieve high removal efficiencies.

The purpose of the carbon adsorption pilot plant is to provide the EPA with a tool for the development of data to fill these gaps. System performance data will be developed to demonstrate the technology for removing VOC from real industrial emissions. The data will also be used to scale up the carbon-adsorption process for comparison with alternative technologies and/or to design the full-scale system.

Carbon adsorption involves three distinct operations—adsorption, regeneration and preparation for adsorption service again. This sequence of operations first removes the VOC from the dilute gas stream and then concentrates the organics in liquid form (via desorption from the carbon and condensation) to facilitate reuse or disposal of the VOC. Note that carbon adsorption does not treat the emission, it only provides a way to concentrate the organics present so that they can be handled by conventional chemical engineering unit operations.

The most widely used adsorption system design has been multiple, fixed beds of carbon with each bed going through the sequence of batch operations described above. The system is designed so that at least one bed is always adsorbing organics from the process emission to provide for continuous emission control. Spent adsorbers are removed from adsorption service, regenerated usually by direct contact with steam and then cooled to prepare them for adsorption service again.

Other approaches to vapor-phase adsorption have been developed but their use has normally been restricted to applications where special considerations are required because of characteristics of the VOC present. These approaches include vacuum regeneration of fixed-bed adsorbers offered by Met-Pro and the PURASIV HR® system (offered by Union Carbide) where a special, beaded activated carbon is moved between a fluidized-bed adsorption zone and a moving, dense-bed regeneration zone. Since both of these technologies have had limited application in the past, the design of the pilot plant should be based on fixed-bed adsorbers. Modifications for novel approaches can be designed and built at a later date as the need arises.

Figure II-1 traces the inlet and outlet concentrations of a fixed-bed adsorber through one complete cycle of adsorption and regeneration. The following objectives are necessary to obtain high removal efficiency:

- Low base-line effluent concentrations. These are usually less than 10 ppm, as shown in Zone 1 of Fig. II-1.
- Containment of breakthrough emissions (Zone 2). This is done by avoiding premature breakthrough or by sending material emitted during breakthrough to another vessel connected in series.
- Efficient recovery of desorbed organics (Zone 3). This is usually achieved by condensing the vapors and recycling the noncondensables from the condenser back to the inlet of the online adsorber.
- Containment of organics exhausted during the cooling and drying cycle (Zone 4). This cycle prepares the carbon bed for renewed

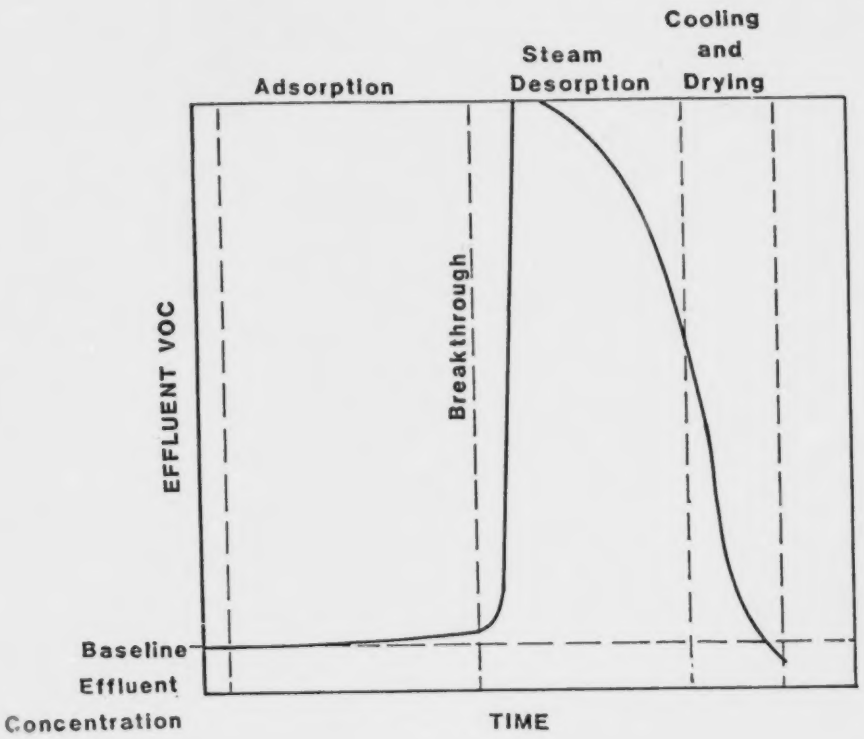


Fig. II-1. Effluent Concentration Profile

service. If a separate cooling and drying cycle is not incorporated in the operation, the cooling and drying will be done during the initial part of the adsorption cycle. This will lead to a high effluent VOC concentration because hot, wet carbon is not an effective adsorbent.

The performance during an adsorption cycle (in terms of adsorption capacity and effluent quality) is influenced by the conditions during the previous steam desorption cycle and cooling and drying cycle. For many existing fullscale adsorption systems this interaction between adsorption performance and regeneration conditions has usually been optimized based on economic factors, e.g., steam consumption was determined by the amount of solvent recovered and no provisions were made for a separate cooling and drying cycle. When low-effluent concentrations are required, the optimization of the interaction between adsorption and regeneration must be based on environmental factors, e.g., enough steam must be used to give a low effluent concentration on the next adsorption cycle and provisions for a separate cooling and drying cycle must be made.

In order to achieve the optimum interaction between adsorption and regeneration, the factors (such as inlet VOC concentration, relative humidity of the inlet waste gas, steam usage and the cooling and drying cycle) that affect the performance of activated carbon during these operations must be understood. The carbon-adsorption pilot plant will give the EPA a tool to help develop an understanding of these factors.

This section of the report describes the criteria for the preliminary design of a carbon-adsorption pilot plant. The design bases are discussed in Part D including the impact of the VOC waste gas characteristics (such as concentration, temperature, humidity, and presence of other materials) on performance and costs. Other design considerations include a discussion of critical process parameters, scale-up, and materials of construction. Part E contains the preliminary process design,

which shows the process flow diagram and process parameter measurement locations. This part also includes a description of the equipment and instruments, as well as the equipment layout, size, and weight estimates. Commercially available equipment is discussed in part F.

B. CONCLUSIONS

1. A carbon-adsorption pilot plant can be designed to evaluate this control device for industrial applications, to develop data to fill the existing gaps described above, and to obtain experimental data (described in Conclusion 4) which can be used in scaling up to larger size systems. Although an off-the-shelf carbon-adsorption pilot plant that would have the flexibility required for this application is not available, the pilot plant can be constructed from commercially available components.

2. Pilot-plant adsorbers that are 1.5 ft in diameter and 3 ft high will be able to handle waste gas containing up to 10,000 ppm_v at a flowrate of 100 cfm. This sizing is suitable to achieve the goals of the pilot plant operation for several reasons. Accurate material balances will be possible because the inevitable losses of VOC from the pilot plant will be a small fraction of the VOC adsorbed each cycle. Also, the pilot plant will be large enough that performance data can be scaled up directly because wall effects will be negligible.

3. Two adsorption beds are needed to demonstrate and evaluate the total process, especially the recycling of the exhaust from the cooling and drying cycle that is required to achieve high removal efficiencies.

4. Experimental data collected from pilot plant studies will allow the calculation of the VOC removal efficiency and adsorption capacity, the optimization of the steam usage and utility requirements, and the determination of additional processing requirements (to purify the recovered VOC or treat the condensate). Other data collected will also allow the determination of carbon life and type of carbon to be used, evaluation

of materials of construction, evaluation of the effect of inlet waste-gas stream characteristics on pretreatment requirements, and determination of the effect of recycling the cooling and drying exhaust on the system performance and costs. This information can be scaled up directly because the pilot adsorbers are large enough to represent a 1.5 ft diameter core from a fullscale adsorber.

5. An important part of scale-up data is the selection of the optimum material of construction in terms of service life and capital costs. The best way to develop these data is to install corrosion specimens in pilot-plant adsorbers made of Teflon®-lined pipe. Teflon-lined pipe is the best choice because the risk of a failure of the adsorbers that would adversely affect the pilot plant schedule and operation is very low. It will also be cheaper to make one set of adsorbers that can be used successfully in almost any service than to make a series of adsorbers out of different materials of construction. Finally the use of corrosion specimens will give the best corrosion data and will allow for the simultaneous testing of several materials.

6. This pilot plant will provide the opportunity for the EPA to develop data on some ways to reduce the amount of dissolved VOC discharged to the sewer with the steam condensate. Although it is beyond the scope of this pilot plant operation to routinely consider evaluation of advanced wastewater treatment technologies (such as aqueous-phase adsorption or steam stripping), it is feasible to evaluate direct reuse of the contaminated steam condensate (as make-up water to the dedicated steam generator) by including a decanter and small hold tank in the pilot plant design. Reusing the VOC-contaminated condensate should have little effect on the steam generator because VOC desorbed from the carbon by steam will also vaporize in the steam generator. The main concern would be the buildup of nonvolatile components (probably generated by hydrolysis of VOC) and the safety aspects of boiling flammable materials. Nonvolatile components can be purged by blowdown of some water at the end of the steaming cycle. Electric immersion heaters should not be used in the steam generator.

7. Including equipment to allow routine evaluation of technologies for upgrading the recovered organics that are decanted from the steam condensate is not practical for this pilot plant. This is because it will be difficult to design a generic system that can accomplish the many different kinds of physical separations that might be encountered. Evaluation of ways to upgrade the recovered VOC should wait until analyses show that such testing is required.

8. The preliminary cost estimate for the carbon-adsorption pilot plant system is $30,000—40,000. The pilot plant system will include the waste-gas blower, filter, cooler, carbon beds, condensers, decanter, steam generator, cooling and drying blower, the trailer, and possibly a chilled water unit. The costs also include adsorption programming system, automatic valves, steel frame work and detailed engineering design. This estimate does not include the cost of analytical equipment.

9. Manpower requirements for the pilot-plant operation will range from one to three people, depending on the nature of the adsorption cycle, the amount of automation incorporated into the pilot plant, and the amount and complexity of the data to be collected. For example, monitoring the operation of the pilot plant and collecting and evaluating the data may at times require only 8 manhours/day. However, there will be cases where 24-hour operation or a large number of analyses will require up to 16 manhours/day more. Estimated manpower costs are therefore $1600 to 4800 per week of operation.

10. The major utility requirement of the pilot plant will be electrical service for the steam generator, chilled water unit, blowers and controls. Electrical service for 90 kWh should be provided. Almost 90% of this electricity is required for the steam generator. Other utilities required are cooling water, instrument air and water for steam generation. Cost of utilities is estimated to be ~$220/week of operation, assuming a 5-day operation, 24 hr/day, and a 2-hr adsorption cycle.

11. The pilot plant will be transported on a 8 ft by 8 ft trailer from which it can be easily lifted. The pilot plant could be placed on the top of a roof with a crane provided the roof can support the weight. The total weight of the pilot plant will be 1000—1500 lb.

C. RECOMMENDATIONS

1. The carbon-adsorption pilot plant should be designed so that data can be generated to fill the existing data gaps as well as to provide a design basis for scale-up to larger systems. Specifically, the design should provide for the evaluation of the effects of relative humidity, steam consumption, recycle of the exhaust from the cooling and drying cycle, and materials of construction on the removal efficiencies, effluent quality, adsorption capacity, and costs. The design should also allow for the evaluation of reusing the steam condensate as a method for reducing the amount of organics discharged to the sewer.

2. Existing off-the-shelf pilot plant designs from carbon-adsorption vendors should not be used because they do not provide the flexibility required to develop the desired data.

3. The pilot plant should have two adsorbers that are 1.5 ft in diameter and 3 ft long and that are made from Teflon-lined pipe. Piping should be included that will allow recycling of the exhaust from the cooling/drying cycle from either adsorber to the other one.

4. The pilot plant should be designed so that critical process parameters can be monitored and controlled. Process parameters of interest include inlet and outlet temperatures, inlet and outlet VOC concentrations, inlet and outlet relative humidities, and the amount of VOC desorbed as a function of steam consumption.

5. Provisions should be made to mount corrosion specimens inside the adsorbers where they will be in contact with the carbon.

6. When reactive compounds such as ketones are present, the safety precautions listed in Section II-D-2 should be followed to avoid conditions that may lead to bed fires in the adsorbers. These compounds should not be excluded from study because satisfactory safe operating experience with them has been achieved when the proper precautions have been followed.

7. It should be recognized that a major reason data gaps exist is that carbon adsorption systems have often received very little attention after they have been installed. The success of the pilot plant in evaluating applications of carbon adsorption and developing data for scale-up will depend in part on the knowledge of the people planning the data collection activities, operating the equipment, and doing the analyses. The people who are assigned to the operation of the pilot plant should understand that carbon-adsorption processes are made up of a group of chemical engineering unit operations. A chemical engineer who is familiar with vapor-phase adsorption should manage the pilot-plant operation and evaluate the data. An analytical chemist should also be involved to direct the development of analytical methods and to provide quality assurance/quality control for the analytical results. For some applications either of these people could also operate the equipment and perform the analyses. When additional people are required, they should be engineers, chemists, or, when appropriate, qualified technicians.

D. DESIGN BASES

1. Description of Waste-Gas Characteristics

Although most VOC can be adsorbed on activated carbon, there are two groups of VOC for which carbon adsorption is not an effective emission control device. High removal efficiencies are difficult to obtain for very volatile VOC because they are not strongly adsorbed by carbon. At the other extreme, it is difficult to achieve effective working capacities and/or carbon lifetimes for VOC with low volatility because they are not desorbed adequately by low-pressure steam. This will increase

the operating costs through increased energy and carbon consumption. If thermal regeneration is required, the operating costs are increased further because savings associated with recovery of the VOC are lost when they are burned during regeneration. Thus the pilot plant design should consider VOC in the following ranges:

a. Molecular weight range of 50 to 200,
b. Boiling point range from 70 to 300°F.

Adsorption temperatures should not usually exceed 90°F because as the temperature increases, both the carbon capacity and the removal efficiency decrease. Water-cooled heat exchangers should normally be installed when the inlet air temperatures exceed 90°F. To keep pilot equipment within a realistic size range, a maximum inlet gas temperature of 250°F for the system was assumed as a design basis.

The VOC inlet concentration to the carbon adsorbers is often limited to 5,000 to 10,000 ppm_v in order to comply with insurance codes requiring that the concentration be maintained below 25% of the lower explosion limit (LEL) and to prevent excessive temperature increases due to the heat of adsorption. Since carbon is a very good thermal insulator, the heat of adsorption can only be removed from the bed by the waste gas itself. If the heat of adsorption is generated faster than it can be removed, the temperature of the bed will increase. This may give poorer adsorption performance as noted above and may lead to the development of hot spots and possibly bed fires if the temperature increase is too high. For these applications, high inlet concentrations are usually reduced by the addition of dilution air which also provides more heat removal capacity. When effective, condensers may also be used to reduce the inlet concentration.

Although carbon is not a good dessicant, the presence of water can adversely affect the VOC removal efficiency and/or VOC adsorption capacity particularly when the relative humidity is above 50%. Since there are very little data that adequately define this phenomenon, the relative humidity should be routinely monitored during the operation of the pilot

plant. No provisions have been made to control the relative humidity but it may be desirable to include equipment to control the relative humidity later.

Pretreatment equipment will be included in the pilot plant so that the effects of contaminants on the performance of the adsorption system can be determined. The inlet stream to the adsorber should be free of most contaminants such as particulates and high boilers because their presence often shortens the useful life of the carbon. Most industrial applications require some type of filtration system to remove the particulates that would otherwise accumulate in the adsorbers and cause an increased pressure drop across them. Since high boilers are not easily desorbed from the carbon by steam, they should be removed to prevent gradual reduction of the overall carbon capacity. Entrained liquids should also be removed via pretreatment because they are already in the concentrated form that the adsorption process is trying to generate and they would therefore needlessly consume adsorption capacity.

2. Safety Considerations

Activated carbon or its impurities catalyze the decomposition of some organics, such as ketones, aldehydes and possibly organic acids and esters. These exothermic decomposition reactions can generate localized hot spots and/or bed fires within an adsorber if the heat is allowed to build up. These hazards will crop up if the flow is low and the inlet concentrations are high, or if an adsorber is left dormant without being completely regenerated.

A fire hazard can also exist during the virgin operating cycle, because there is little water present on the carbon to act as a heat sink and because more material is adsorbed during this cycle than during other cycles.

These considerations do not mean that vapor-phase adsorption should not be selected for these potentially hazardous applications, but rather that safety and performance require compensation for hazards in the

adsorber design and operation. For example, the careful choice of activated carbon and operating procedures has enabled General Tire and Rubber Co. to recover methyl ethyl ketone from its fabric coating operations for over 15 years without incident.(2)

To reduce the hazard of bed fires, the following procedures (3) are usually recommended:

a. The bed should never be left dormant unless it has been thoroughly regenerated.
b. Design parameters should be set so as to avoid high inlet concentrations and low flows.
c. Instrumentation, including alarms, should be installed to monitor the temperature change across the adsorber bed and the outlet CO/CO_2 concentrations. The instrumentation should signal the first signs of decomposition, so that any acceleration leading to a bed fire can be forestalled.
d. A deluge system should be provided to water-cool the bed in the event of an excursion.
e. A virgin bed should be steamed before the first adsorption cycle. The residual condensate will provide a heat sink.

3. Scale-up Considerations

Accurate scale-up of any chemical engineering unit operation requires understanding the relationship between the performance observed in pilot-scale equipment and the performance that can be achieved in full-scale systems. Understanding this relationship requires two things:

a. Appropriate reproduction of the conditions expected in the full-scale system during the pilot-scale tests.
b. Definition of the factors that cause differences in performance observed between small and large equipment even when conditions are accurately reproduced.

For vapor-phase adsorption, pilot-scale adsorbers will usually perform almost exactly like full-scale systems operated under the same conditions (superficial velocity, inlet VOC composition, relative humidity, temperature) if the pilot adsorber is the same depth as the full-scale adsorber and is large enough in diameter (usually greater than 2 in.) to overcome wall effects. This is because the pilot adsorber accurately represents a cylindrical section out of a full-scale adsorber. Also, parameters that affect the direct scaleability of pilot data for other unit operations (such as surface-to-volume ratios or completeness of mixing) do not affect the performance of vapor-phase adsorbers. Thus, when the pilot adsorber is appropriately sized, the scaleability of adsorption data developed by this pilot plant will most often be related to the reproduction of conditions expected in the full-scale adsorber.

4. Critical Process Parameters

A pilot plant study of a carbon adsorption system should include the determination of the following parameters.

a. Removal Efficiency——The concentration of VOC in the inlet waste gas stream and the system outlet stream should be measured to determine the overall efficiency of the control device. Also, both concentrations should be measured so the operating capacity of the carbon can be determined. Enough samples should be taken during the adsorption cycle so that variations in the inlet and outlet stream profiles can be determined. The best and most versatile analytical method for measuring for specific organics is gas chromatography. The choice of the sample collection methods (manual or automatic) will depend on the specific application. Automatic sampling and analysis should be considered to collect samples rapidly when the adsorption cycle is short (up to 1 hr) or to provide semi-continuous monitoring when the adsorption cycle is long.

b. Carbon Capacity——The working capacity of the carbon is usually 25 to 50% of the equilibrium isotherm adsorption capacity of the carbon for several reasons. First regeneration, even exhaustive regeneration,

will not remove all the adsorbate. Second, isotherms are measured or predicted for pure compounds. They do not measure the impact of other VOCs and/or water on adsorption capacity. Third, an adsorber is a dynamic system in which equilibrium cannot be achieved.

One method of determining the operating capacity is to calculate it from material balance by measuring the inlet and outlet concentrations, the flow rate to the system, and the length of adsorption cycle. This measurement should be checked by measuring the amount of organic that is removed from the bed during regeneration. When this check is made, other ways that the adsorbed materials can leave the adsorption system should be measured in order to close the total material balance. The working capacity will need to be measured for a series of adsorption/desorption cycles made at the same conditions. When a stable working capacity is established (usually in less than 5 cycles), the effect of different adsorption or desorption conditions on working capacity can be determined by completing another series of adsorption/desorption cycles at the new conditions.

c. Carbon Lifetime—The ability to reuse the carbon for many adsorption cycles is crucial to developing an economic application of adsorption. Demonstration of an acceptable carbon lifetime (by showing that a stable working capacity can be achieved) should be a goal of any pilot-plant evaluation. If a stable working capacity cannot be achieved, the reasons for this should be determined. The carbon life may also depend on the ability to maintain acceptable VOC effluent concentration. Hopefully, enough adsorption/desorption cycles can be completed during a pilot-plant study to demonstrate that acceptable effluent quality can be maintained and to determine the requirements for doing so.

d. Type of Carbon——The performance of an adsorption system will sometimes be affected by the type of activated carbon used. The pilot plant can be used to evaluate types of carbon for a specific application. When different carbons are to be evaluated in the pilot plant, all the tests should be completed on each carbon before it is removed. Since the performance of an adsorber is also influenced by the history of the

carbon itself, removing the carbon and then reusing it may introduce a variable that would not be reproduced in the full-scale system. Also it is likely that different results will be obtained when the pilot plant is refilled with used carbon than if carbon remained in the adsorber because used carbon in an adsorber is rarely homogeneous. Usually the carbon at the inlet end has more residual materials than the carbon at the outlet end. In fact it is the maintenance of "clean" carbon at the outlet end due to this staging effect that allows the achievement of low effluent concentration. Thus, it is inevitable that the arrangement of carbon in an adsorber with reused carbon will be different than in the original adsorber.

e. Steam Usage——Steam is the most common regenerating agent used because it is easily condensed, readily available, inexpensive, and a concentrated source of heat. Steam provides the energy necessary to heat the carbon and the vessel up to the desorption temperature and provides the heat of desorption. However, most of the steam is actually required as a mass-transfer medium to promote desorption by maintaining a concentration gradient between the carbon and the bulk-phase fluid in the bed. This concept is illustrated in Fig. II-2 which shows a typical relationship between the cumulative amount of VOC desorbed (as a fraction of VOC that can be desorbed by exhaustive steaming) and the cumulative amount of steam used per pound of carbon. Note that no VOC is desorbed until a finite amount of steam (usually about 0.20 to 0.25 lb steam/lb carbon) has been used. Note also that significantly more steam is required to achieve 100% desorption than to achieve 90% desorption. Thus the amount of steam used affects the working capacity that is established.

The amount of steam used also affects the effluent concentration that can be achieved in the next adsorption cycle. If data were available on this phenomenon it would probably be similar to the hypothetical data shown in Fig. II-3.

Data on both the relationships discussed above should be generated for each application of the pilot plant because very little data are available. This requires measurement of the steam flowrate to the adsorber,

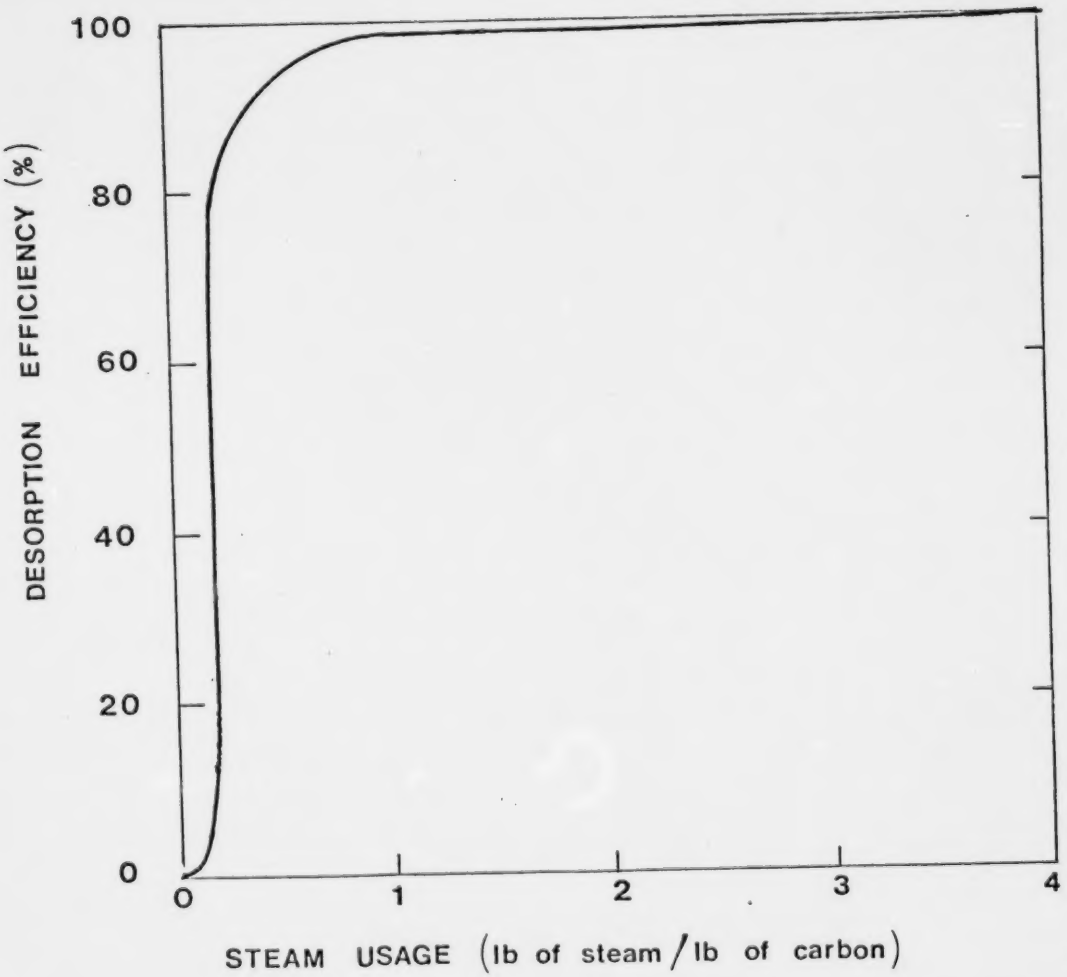


Fig. II-2. Desorption Efficiency Based on Steam Usage

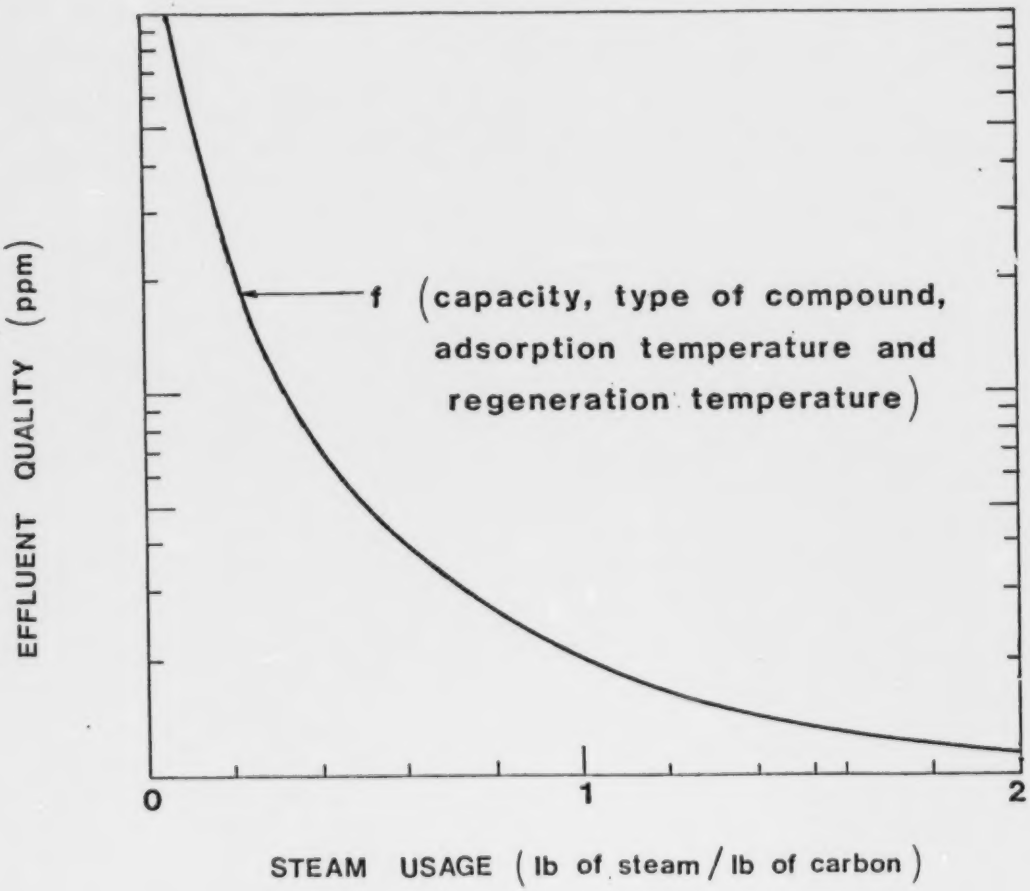

EFFLUENT QUALITY (ppm)
f (capacity, type of compound, adsorption temperature and regeneration temperature)
0
1
2
STEAM USAGE (lb of steam / lb of carbon)

Fig. II-3. Effluent VOC Concentration Based on Steam Usage

which is most easily done by generating steam specifically for the adsorber rather than trying to meter plant steam.

f. Temperature——Generally higher temperatures give lower adsorption capacities but this effect is most pronounced over large temperature ranges. Usually adsorption temperatures below 90°F give adequate performance. If for a particular system there is a possibility that the waste-gas temperature will change, the effect of temperature should be determined so that the need for coolers can be evaluated.

Each adsorber should have a temperature indicator and recorder on the inlet and the outlet. This will provide important data for the temperature profiles for the adsorption, desorption and cooling/drying cycles that will be very helpful in monitoring each of these cycles.

g. Pressure Drop——The pressure drop across the carbon bed should be measured in a pilot plant study so that the blowers can be properly sized. An increase in the pressure drop as the pilot plant studies progress may indicate that plugging of the bed is occurring and a more efficient particulate filter may be needed.

h. Optimum Adsorption Cycle——The optimum lengths of each part of the total adsorption cycle should be determined so that they can be specified in the full-scale design. The minimum cycle time should be two hours to allow enough time for adequate desorption and cooling and drying. For applications with low inlet VOC concentrations, the adsorption cycle will be longer and allow some flexibility in specifying the lengths of the desorption and cooling and drying cycles.

5. Process Optimization

There is often an opportunity to optimize a carbon-adsorption application because of the flexibility in design that usually exists. Process optimization is often possible in the following areas.

a. Sizing the Adsorber——There is usually some flexibility in sizing an adsorber, since two factors will be balanced: (1) there must be enough

carbon for an adequate and effective adsorption cycle, and (2) cross-sectional area must be sufficient to prevent excessive pressure drop across the bed. Thus, adsorber sizes are limited either by the mass flowrate of the organics and the working capacity or by the volumetric flowrate and the depth of the bed.

Applications limited by adsorption capacity are usually characterized by high inlet concentrations. Capacity must be large enough to allow adequate time for the spent adsorber to be desorbed, cooled and dried. Although systems with adsorption cycles of 1 hr have been installed, they provide little flexibility for operational changes that improve performance or increase throughput. If possible, new systems should be sized to contain enough carbon for at least 2 hr of adsorption, normally an adequate time for the carbon to be regenerated and prepared for adsorption service again.

Pressure-drop considerations usually govern the selection of bed height and cross-sectional area because the pressure drop is influenced by linear velocity and bed depth. Since centrifugal fans are used to move the air, the allowable pressure drop is limited to ~20 in. of water, and cross-sectional areas are designed for linear velocities of 50 to 100 fpm. Bed depths then usually range from 12 to 36 in. The appropriate vessel size can be determined straightforwardly from the volume of carbon, linear velocity, bed depth, and pressure drop.

When inlet concentrations are high, a relatively large volume of carbon is required. Since the bed depth is fixed over a narrow range, the cross-sectional area dictated by this large volume of carbon usually results in a linear velocity at the low end of the range 50 to 100 fpm. Vertical cylindrical vessels are favored for small flows. For large flows, horizontal vessels offer an alternative to fabricating short, large-diameter vertical vessels.

Some additional design flexibility is available if the emission is under pressure before discharge, as is the case in many oxidation reactions that use air as the source of oxygen. Higher linear velocities and/or deeper beds are possible when a higher pressure drop can

be taken across the adsorber. The advantage is a smaller adsorption system, since more of the volume inside the vessel is filled with carbon.

Flowrate poses a restriction when it is high and the inlet concentrations are low (usually below 1,000 ppm). This situation often occurs when ventilation is needed inside the equipment to keep the organic concentrations below the lower explosion limits mandated by fire and/or insurance codes. Dilute emissions also occur in odor control, and in installations specified to meet workplace concentrations set by OSHA regulations.

In these cases, adsorbers are sized primarily for handling a large flow at a low pressure drop. If the linear velocities must be limited to 100 fpm, the vessel is usually much larger than that indicated by the adsorption duty. Even though bed depths of 6 in. or less will yield an adsorption cycle of 2 hr or more, deeper beds are often used if the pressure drop will allow it. The incremental cost of adding more carbon to a large vessel is more than offset by the added flexibility that a longer adsorption cycle gives.

b. Initiation of Desorption Cycle——The optimum combination of achieving high removal efficiencies and efficient utilization of steam and carbon occurs if desorption is initiated when breakthrough is detected. If desorption is initiated after breakthrough occurs, overall removal efficiencies are reduced. If desorption is initiated before breakthrough occurs, high removal efficiencies will be achieved but there could be increased costs associated with less efficient use of steam and the adsorption capacity that is available. In the past, however, the savings associated with increased solvent recovery, higher removal efficiencies and optimum utilization of steam and carbon did not justify the additional costs required for online monitoring. Thus, many existing full-scale adsorption systems use timers to initiate the desorption cycle.

However, the recent emphasis on achieving high removal efficiencies has increased the importance of preventing the emissions of VOC due to breakthrough (Zone 2 in Figure II-1). Thus, for applications where high removal efficiencies are desired, timers may be appropriate only when the characteristics of the waste-gas streams (flow rate and VOC concentrations) are consistent and reproducible so that breakthrough can be accurately predicted based on time. Data needed for this optimization that should be generated during the operation of the pilot plant include definition of the breakthrough curve and characterization of the waste-gas stream.

c. Adsorption Performance Versus Regeneration Conditions——The performance during the adsorption cycle (in terms of removal efficiency, VOC outlet concentration, and working capacity) is a function of the condition of the carbon which in turn is related to the conditions used during the desorption cycle and the cooling and drying cycle.

The optimum steam consumption will be determined from data like that shown in Figures II-2 and II-3. Since these data are not readily available for many VOC, they should be generated for each application of the pilot plant. When the effect of steam consumption on VOC outlet concentration is defined, several adsorption/desorption cycles at the new steam usage should be completed so that the new equilibrium conditions can be established.

d. Removal of Contaminants——Frequently the waste-gas stream will contain components that affect the ability of the carbon to achieve and/or maintain good performance. As discussed previously, these materials can include high boilers, water, particulates, and aerosolized liquids. The pilot plant operation should be monitored so that adverse effects of any of these components can be detected and quantified. This will provide the data base necessary to decide if the design of the adsorbers should be modified to account for the adverse effects or if pretreatment equipment should be included to remove the contaminants.

6. Pretreatment Equipment Required for the Pilot Plant

Selection of the pretreatment equipment that should be included in the pilot plant design requires striking a balance between the benefits of expanding the capabilities of the pilot plant to include all situations and the costs of including equipment that might be rarely used. A suitable compromise might be to specify the equipment for all or most of the pretreatment options but only purchase the specific pieces of equipment when they are needed.

The following pretreatment options should be considered during the pilot-plant design.

a. Filtration——A filter should be included in the pilot-plant design because particulates are present in enough potential applications of carbon adsorption. A disposable filter would be adequate for most applications but the filter should be selected so that filter media with different removal efficiencies could be used.

b. Waste-Gas Cooling——A cooler should be included in the pilot plant design because many waste gases will have temperatures above 90°F. The cooler should be designed to cool 100 cfm from 250 to 90°F using cooling water or plant process water as the coolant. These sources of water will be available at most plant sites where the pilot plant will be operated. A water chiller will be required only when the ambient water temperature is too high to give adequate cooling. A cooler designed to use dry ice could be an alternate to a water chiller.

c. Addition of Dilution Air——Frequently, dilution air is mixed with the waste gas to reduce the adsorber inlet VOC concentration and/or to provide cooling capacity to remove the heat of adsorption. The capability to separately meter the dilution air should be included in the pilot plant.

d. High Boiler Removal——When high boilers are present, they can shorten the lifetime of the carbon because they are not removed during the desorption cycle. Sometimes pretreatment to remove high boilers can be a cost-effective alternate to more frequent changes of the carbon.

Partial removal of high boilers will be achieved by cooling the waste gas. If this is not adequate, a sacrificial adsorption bed can be used ahead of the adsorbers to separate the high boilers from the waste gas. The decision on including a sacrificial adsorber in the pilot plant has been deferred because it will depend on the types of waste gases on which the pilot plant will be used.

e. Entrained Liquids Removal——Removal of entrained liquids via pretreatment can be cost effective because the adsorption duty is increased (often needlessly) by the presence of VOC that are already in a concentrated liquid form. Entrained liquids, except for aerosols, can be removed by demisters. If aerosols are present, addition of dilution air as described above or elimination of the aerosols at the source are the best alternates.

f. Dehumidification——Pretreatment equipment should not be included in the pilot plant design unless there are enough potential applications where the relative humidity will be above 50%.

Although there are very little data, it is known that increasing relative humidity (especially above 50%) can adversely affect the performance of a carbon adsorber. Including equipment to dehumidify the waste-gas prior to adsorption would expand the capabilities of the pilot plant. The EPA should decide if there will be enough pilot-plant applications on humid waste gases to justify including dehumidification. If dehumidification is included, independent control of the inlet temperature should be provided also.

7. Separation Equipment Required for the Condensate from the Desorption Cycle

As discussed before, carbon adsorption by itself does not control VOC emissions or recover VOC. Carbon adsorption only removes VOC from the waste gas and concentrates them so that they can be handled by other unit operations. Therefore, in addition to evaluating the performance of the activated carbon itself, the pilot-plant operation must also consider the treatment and disposal of the condensate generated during the steam desorption cycle for two reasons. First, scale-up data must

be available for the design of the full-scale system. Second, the wastes generated by the pilot plant must be properly treated prior to disposal.

A decanter should be installed in the pilot plant to separate the bulk of the water from the bulk of the condensed VOC and to determine the compositions of the aqueous and organic streams. However, direct reuse of the aqueous-phase from the decanter (as make-up water for the dedicated steam generator) is the only wastewater treatment technique that can be justified for inclusion in the pilot plant design now. Direct reuse of the VOC-contaminated condensate will be a cost-effective way to "treat" this wastewater because it will not increase the energy consumption. Since most VOC desorbed from carbon will boil before water boils in the steam generator, direct reuse also provides a way to separate most of the VOC from most of the water. The potential drawbacks of this approach are a buildup of nonvolatile materials in the steam generator and a lower desorption efficiency due to the use of contaminated steam as the desorption fluid. Buildup of nonvolatile materials can be avoided by "blowdown" of some water at the end of the steaming cycle. Use of contaminated steam should have a minimal effect on the desorption efficiency since clean steam will be available at the end of the cycle when it is needed most because most VOC in the condensate will vaporize early in the desorption cycle.

It is not feasible to include any additional separation equipment until the nature of the applications of the pilot plant is better defined because the unit operations required are a function of the physical properties of specific organic compounds, especially solubility of water in the organic and of the organic in water. For example, for some applications steam stripping or aqueous-phase carbon adsorption may be required to remove organics from water prior to discharge. In other cases, distillation may be required to upgrade the recovered organic for recycle and reuse. When additional unit operations are required to treat the organic-water mixtures, scale-up data for design will be developed from two sources. For applications with common VOC, the composition of the

streams from the decanter will be sufficient for designing a full-scale system. However, there will also be times when testing of additional unit operations is needed in order to generate appropriate design data. Initially this testing should be done in the laboratory until actual experience shows that the installation of additional unit operations to the pilot plant can be justified.

8. Materials of Construction

The materials of construction for the pilot-plant adsorbers should be selected so that they can be used reliably in almost any application. This premise dictates that the adsorbers be Teflon-lined because many metals experience accelerated rates of corrosion when they are in contact with carbon due to the establishment of galvanic cells. Use of other lining materials is not suitable because they are not compatible with as many different kinds of VOC. Maintaining the bond between the Teflon liner and the substrate in services requiring thermal cycling is difficult because of the difference between the coefficients of thermal expansion of the Teflon and of the substrate. Therefore Teflon-lined pipe should be used for the adsorbers because the method of anchoring the Teflon liner to the pipe is the best way to prevent premature failure of the liner.

The pilot plant should also be capable of generating data that can be used as guides in the selection of proper materials of construction for the full-scale system. Therefore provisions should be made to insert several corrosion specimens in the adsorber in contact with the carbon so that comparative corrosion data can be collected. The corrosion specimens should be small flat plates mounted so that the plane of the plate is parallel to the vertical axis of the adsorber. This configuration will minimize the chance that the corrosion specimens will cause channeling.

E. PRELIMINARY PROCESS DESIGN

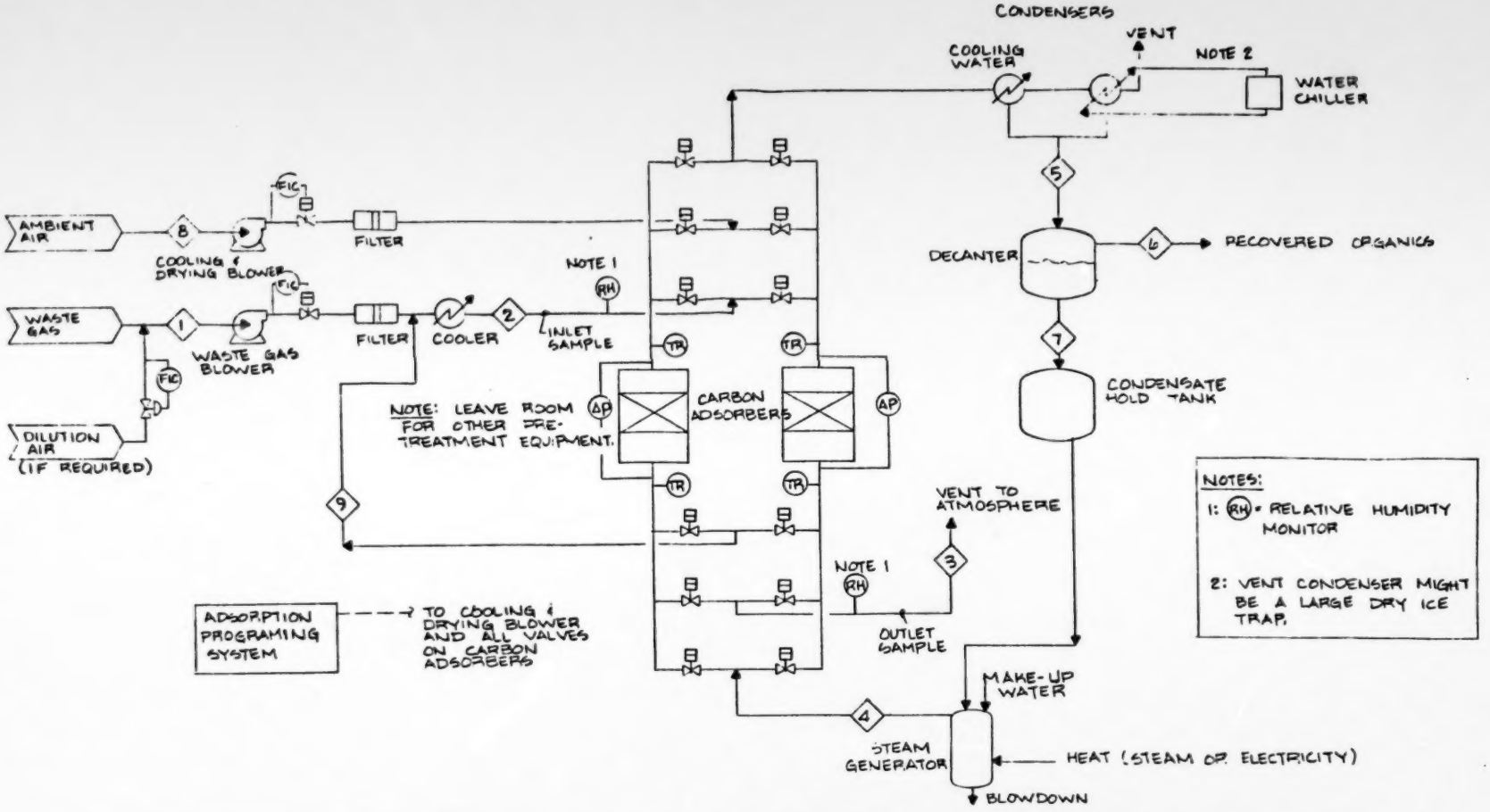
1. Process Description

The pilot plant system should be capable of handling a waste-gas flow rate of 100 cfm with a maximum VOC concentration of 10,000 ppm at

temperatures up to 250°F. The pilot-plant system is shown in Figure II-4. The material balance is based on treating a waste gas containing 100 to 10,000 ppm VOC at a flowrate of 100 cfm. The flows of steam and condensate during regeneration are based on steaming from 50 to 150 lb carbon at a rate of 1 lb steam/lb carbon during a 1-hr cycle. The organic flow from the decanter will be related to the amount of VOC desorbed (which is a function of the loading) and the period of time in which the desorption occurs. Figure II-2 shows that most of the VOC is desorbed early in the cycle. The maximum flow shown in the material balance for stream 6 is based on a loading of 0.2 lb VOC/lb carbon and a time interval of 20 minutes. The zero flow condition for the organic layer from the decanter will occur at the end of the steaming cycle when the amount of VOC desorbed is not enough to saturate the water layer.

The waste-gas blower will provide the pressure necessary to move the waste gas through all the pilot-plant equipment. The waste gas will be filtered and cooled before it is introduced into one adsorber where the VOC will be removed from the air. When desorption is initiated (either by a timer or by detection of breakthrough), the waste gas flow will be diverted to the other adsorber and steam will be passed through the "loaded" bed to remove the adsorbed VOC. Two condensers operated in series will be used to liquify the steam and the desorbed VOC. Most of the condensation will occur in the first condenser which is cooled by water. A second condenser will function as a vent condenser. It will be needed most when the collection efficiency of the first condenser is poor because of high cooling water temperatures (as in the summer) or by the low boiling points of the VOC in the system. The condensate will be collected in a decanter to provide separation of insoluble organics from the water. Disposition of each stream will depend on the specific application.

Ambient air will be used to cool and dry the adsorber when the desorption cycle is complete. The hot, wet exhaust will be recycled to the online adsorber (by mixing it with the waste gas upstream of the inlet cooler) until the VOC concentration is low enough to allow venting to the atmosphere. When the cooling and drying cycle is complete, the adsorber will be ready to go in adsorption service to allow for regeneration of the other adsorber.



STREAM No.		WASTE GAS (1)	INLET WST GAS (2)	EFFLUENT GAS (3)	STEAM (4)	COND. (5)	ORG LAYER (6)	WATER LAYER (7)	COOL & DRY AIR (8)	COOL & DRY EXHAUST (9)	
FLOW	scfm	100	100 or 140	100 or 140	50-150 lb/hr	0.1-0.5 gpm	0-0.07 gpm	0.1-0.5 gpm	40	40	
CONC.	ppm	100-10,000	100-10,000	0-100	100% H_2O	2-15% ORG.	50-100% ORG.	0-10% ORG.	0	0-100	
TEMP	°F	≤ 250	70-90	up to 90	212	≤ 90	≤ 90	≤ 90	AMBIENT	>100	
PRESSURE		?	≤ 20 in H_2O	0 in H_2O	~ 0 psig				≤ 9 in H_2O	≤ 20 in H_2O	

SUBJECT	CARBON ADSORPTION PILOT PLANT
	FLOW DIAGRAM
PAGE	1 of 1
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BY	H. BASDEKIS / C. PARMELE
DATE	1/20/81

Figure II-4. CARBON ADSORBER PILOT PLANT

The pilot plant should be designed so that the repetitive cycling can be done either manually or automatically. This would provide the flexibility required to adapt the pilot plant to each application. It would also provide the capability to generate data efficiently during evaluations (such as the determination of carbon lifetime) when the pilot plant operation is repetitive.

2. Equipment List

a. Waste-Gas Blower——The waste-gas blower should be able to move 100 cfm through the pilot-plant system. The blower should be able to overcome a total system pressure drop of up to 20 inches of water. Materials of construction should be selected to give the most flexibility in a service that would include many different vaporized solvents in air at temperatures up to 250°F.

Provisions should be made to add dilution air to the inlet of the blower when necessary to prevent an increase in carbon-bed temperatures due to heat of adsorption. Instrumentation should be included to control and monitor the flowrate of the dilution air and of the blower outlet to the adsorber.

b. Inlet Filter——This filter should have a disposable filter media that would achieve 85% removal efficiency. Flow capacity should be 100 cfm at a pressure drop of no more than 1 inch of water.

c. Inlet Cooler——This cooler should be able to cool the inlet waste-gas from 250°F to 90°F. The cooler should also be able to cool the exhaust of the cooling and drying cycle to 90°F. This cooler should also have provisions for draining condensate that will be generated occasionally. Pressure drop across the cooler should be no more than 1 to 2 inches of water. Materials of construction should be selected in the same way they were for the waste-gas blower.

d. Carbon Adsorbers——The adsorbers should be made from 1.5 ft diameter Teflon-lined steel pipe. They should be 3 feet high and have provisions for installing corrosion specimens in contact with the carbon. The adsorbers should be designed so that the carbon can be easily replaced. Each carbon bed should also be insulated to minimize heat losses during the steaming cycle.

e. Steam Generator——A steam generator should be included to facilitate measurement of both the rate and total consumption of steam used for desorption (in order to generate the data shown in Figures II-2 and II-3). The steam generator should also be able to use condensate from the decanter as makeup water so that direct reuse of the condensate (containing organics) can be evaluated as an approach to wastewater treatment and water reuse. This will affect the selection of the materials of construction and will require that provisions be made to safely boil water containing organics.

The steam generator should be able to contain 20-25 gallons of water and to generate steam at rates up to 150 lb/hr at a pressure of 5 psig so that up to 1 lb steam/lb carbon can be consumed during a one-hour desorption cycle when the pilot-plant adsorber contains 143 lb carbon (equivalent to a bed depth of 3 feet in the 1.5 ft diameter pilot-plant adsorber).

f. Condensers——Two condensers should be used to condense the steam and desorbed VOC. The first condenser should be large enough to condense up to 150 lb/hr of steam. The second condenser will function as a vent condenser that can be a conventional condenser cooled by chilled water as shown in Figure II-4. Some capital costs could be saved by designing the condenser as a large dry ice trap.

g. Decanter——Several criteria need to be considered in designing the decanter. It will be desirable to monitor the rate at which water-insoluble organics are desorbed in order to generate desorption efficiency data similar to the data in Figure II-2. It will also be

desirable sometimes for the decanter to automatically separate water and organics with little attention from the operator. Finally, when reuse of the condensate is being evaluated, it will be necessary to save the aqueous phase for the next desorption cycle. One way (but not necessarily the best way) to design the decanter is to use a small continuous decanter (capable of decanting up to 150 lb/hr or 18 gal/hr water) that would discharge the organic phase into a graduated 2 gallon vessel and the aqueous phase into a 20 gallon tank. A glass vessel for the organic phase would facilitate measuring the rate of accumulation of the desorbed VOC but the safety aspects of using glass in a service with flammable materials would have to be scrutinized.

h. Cooling and Drying Blower——The capacity for the cooling and drying blower should be 40 cfm. A flowrate of 40 cfm for the cooling and drying air represents a compromise between cycle time and pressure drop. A higher flowrate would give a shorter cooling and drying cycle but would increase the pressure drop across the adsorber that was in the adsorption mode because of the higher superficial velocity. A lower flowrate would have less impact on the pressure drop across the online adsorber but would also give a longer cooling and drying cycle.

The pressure drop that the cooling and drying blower should be able to overcome is 20 inches H_2O because the cooling and drying air will go through both adsorbers. Assuming that 4 X 10 mesh carbon is used, the pressure drop data in Fig. II-5 show that the pressure drop across the adsorber in the cooling and drying cycle will be $\sim$3 inches H_2O and the pressure drop across the adsorber in the adsorption mode will be $\sim$15 inches H_2O.

Provisions should be made so that the blower can be started either manually or by the automatic sequencing system. Materials of construction should be compatible with ambient air. A filter similar to the one used for the waste gas should be installed with this blower to keep atmospheric dust out of the adsorbers.

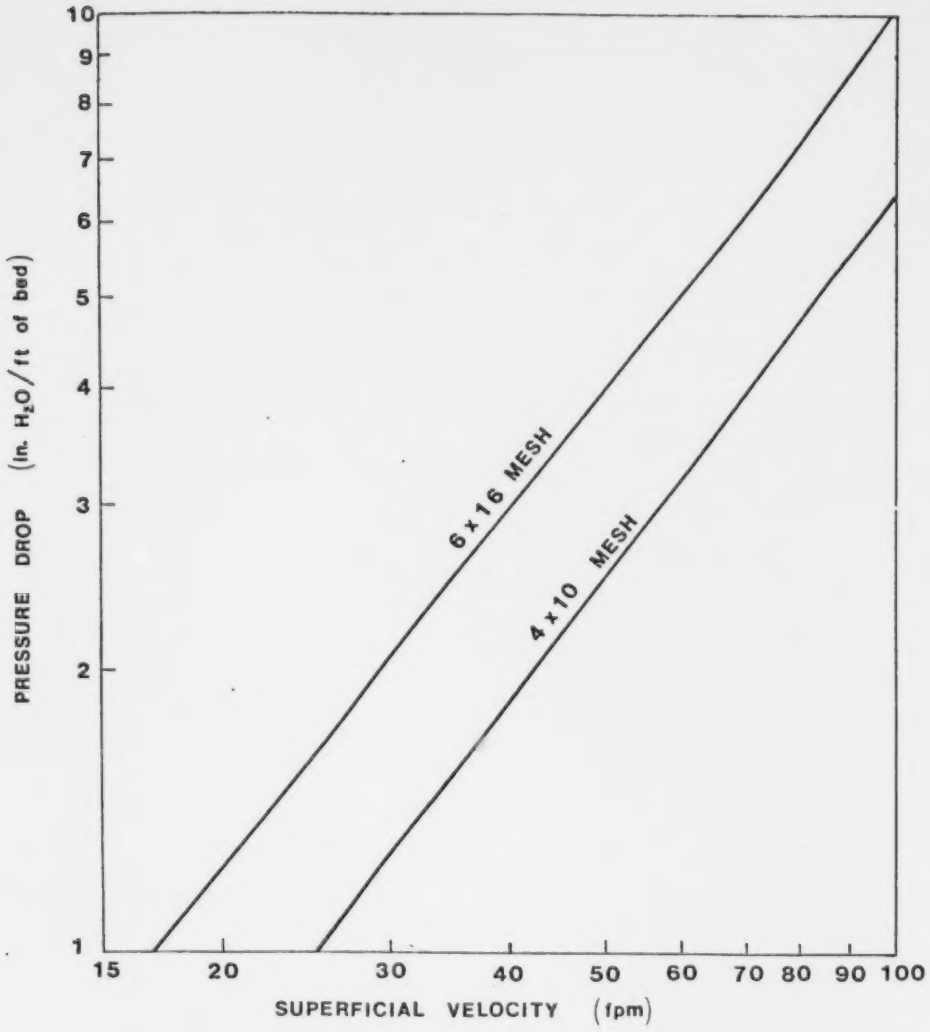


Fig. II-5. Bed Pressure Drop for BPL Carbon

i. Valves for the Adsorbers——The valves should be leak-proof and compatible with the thermal cycling nature of this application. Leaks cannot be tolerated because they can give erroneous information regarding the composition of various streams. For example, if the cooling and drying exhaust from one adsorber leaks into the vent to the atmosphere, it would appear that the online adsorber has more VOC in its outlet than is really present. The valves should be equipped with operators so their positions can be changed automatically by the automatic sequencing system.

3. Instruments and Controls List

a. Adsorption Programming System——Vapor-phase adsorbers are often operated by an automatic programmer. Such a programmer should be provided for the pilot plant so that the adsorption, desorption, and cooling and drying cycles can be initiated automatically. However, the programming system should be designed so that the pilot plant can be easily operated in the manual mode.

b. Controlled Process Streams——Instrumentation should be included to control the waste-gas flowrate to the adsorbers and the flowrate of the cooling and drying air to the adsorber and flowrate of dilution air.

c. Monitored Process Streams——Instrumentation should be included to monitor the following process parameters.

- Adsorber inlet and outlet temperatures
- Waste gas temperature before and after the inlet cooler
- Relative humidity of the adsorber inlet and outlet
- VOC concentration of the adsorber inlet and outlet
- Composition of the organic and aqueous streams from the decanter

A multipoint temperature recorder should be used to follow the temperature profiles because it is an excellent way to monitor and verify the overall process sequence. Routine measurements of relative humidity are facilitated by an on-line instrument. Measurement of VOC concentration should be done with a gas chromatograph equipped with gas

sampling loops. Sampling can be done manually or automatically depending on the application.

Analysis of the two liquid streams from the decanter will be done by gas chromatography. Sampling requirements will depend on the application.

4. General Construction Guidelines

The adsorption pilot plant will often be operated at ground level on the trailer on which it is transported. However, it will not always be possible or practical to operate the pilot plant on the ground because of the location of the waste-gas exhaust from the plant. Sometimes it will be better to install the pilot plant on the roof or in the plant instead of installing duct work to bring the waste gas to the pilot plant at ground level. Therefore, the framework for the skid should be made from extra heavy steel that is welded together so that the pilot plant can be easily moved by overhead cranes or fork lift trucks.

The equipment shown in Figure II-4 can be easily installed so that it will fit in an 8 ft x 8 ft area and be no more than 8 feet high.

5. Estimated Requirements for Operation

a. Utilities——The pilot plant will require electricity, water, instrument air and possibly steam. The motors on the blowers, the motor on the water chiller (if one is installed) and the adsorption programming system will require 110 volt service. If an electrical steam generator is used, additional service (probably 220 volt) will be required. All of the electrical equipment should be both explosion proof and waterproof so that the pilot plant can be used in hazardous and/or outside areas.

Cooling water will be required for the inlet cooler (1-2 gpm) and the main condenser (~10 gpm). Process water will also be needed for the steam generator (~20 gallons per regeneration).

If steam is used as the energy source for the steam generator, it should be available at 150 lb/hr at a pressure of at least 15 psig.

b. Manpower——Actual operation of the pilot plant requires only a small proportion of the total manpower for a pilot-plant evaluation because most of the manpower is used to analyze samples to generate the data. Therefore the manpower requirement is really a function of the quantity and complexity of the analyses needed and the amount of automated operating and analytical equipment that is included in the pilot plant. For applications where only one compound is present and the adsorption cycle is 2 to 4 hours long, one person can do most of what is required; however, one or two more people will be required for pilot-plant applications when the analyses are more complex, when shorter adsorption cycles require more frequent sampling, or when larger adsorption cycles require operations for more than one shift.

The duration of a pilot plant evaluation will be a function of the amount of data to be collected and the length of the adsorption cycle. Often a pilot plant evaluation will require 20 to 30 cycles in order to determine optimum conditions and then to test the effect of changing regeneration or feed conditions on loading or effluent quality.

F. COMMERCIALLY AVAILABLE EQUIPMENT

An off-the-shelf pilot-plant unit can be an attractive approach to obtaining a pilot plant but it is not recommended for this operation.

Carbon adsorption equipment vendors usually rent, not sell, pilot plant equipment to potential customers. Only one equipment manufacturer contacted has an off-the-shelf pilot plant that they would sell. Hoyt Manufacturing's pilot plant equipment includes a 500 cfm single tank adsorber with 300 pounds of carbon, blower, condenser, decanter and manual controls. The pilot plant cost is around $6000. This pilot-plant should not be used because it does not offer the flexibility and capabilities required for this application.

Although an off-the-shelf unit is not available, many carbon adsorption equipment manufacturers will build a packaged pilot plant system to the specifications one would want. This is probably the best approach because it will utilize their experience in constructing skid-mounted adsorption systems, which should be particularly valuable in specifying the adsorption programming system and the structural design.

The companies contacted who would build a unit as described in this report are Vic Manufacturing, Hoyt Manufacturing, Vulcan Cincinnati, and Clermont Engineering. Ray-Solv will not build this pilot plant unit because the smallest system they build will handle 10,000 cfm.

The estimated cost for this pilot plant system of $30,000 to 40,000 was derived from discussions with several vendors. This price includes all the equipment shown in Figure II-4 and the trailer on which to load the adsorption skid.

III. THERMAL OXIDATION PILOT UNIT

A. GENERAL

For the past few years the EPA has been investigating direct flame incineration (thermal oxidation) as a part of their overall program for identifying the best available technology for the control of VOC emissions. The investigations include the acquisition of data from laboratory and full-scale operating incinerators, evaluation of destruction efficiency data, and consideration of capital cost and energy use.

One of the problems identified by the investigations is the lack of a well-defined scientific basis for the design of full-scale incinerators.(4) Because of apparatus design limitations and the need to control the number of variables, laboratory-scale systems tend to give idealized performance which can be described by first order reaction kinetics. The operation of full-scale systems appears to be considerably more complex and not adequately described by the laboratory data. There is a need therefore to obtain data that can be used as the bases for design of cost-effective full-scale systems.

The purpose of the pilot thermal oxidation unit is to provide equipment by which representative process data can be obtained under conditions which approximate or simulate full-scale operation. The pilot unit is intended for investigation of the various process parameters which affect thermal destruction efficiency and equipment and operating costs.

This report section identifies the preliminary requirements for the detailed design and specification of a pilot thermal oxidation system with recuperative heat recovery. It includes a discussion of the design bases such as VOC characteristics, critical process parameters, equipment scale-up considerations, safety requirements, transportability and operation. A very preliminary process design is presented in block flowsheet form and the major components are briefly described in equipment and instrument lists. The cost of purchasing a pilot unit is

estimated and the applicability of commercially available equipment is discussed.

B. CONCLUSIONS

1. Pilot Unit Applications

Most potential VOC control applications will involve dilute organic concentrations (<13 Btu/scf) in air with sufficient oxygen for combustion. The pilot unit, however, should be designed to handle both dilute emissions as well as high concentration organic waste in oxygen-deficient or inert streams. The pilot unit should also be capable of controlling halogenated VOC and sulfur-containing waste streams. Typical applications include the control of solvents from surface coating operations and emissions from chemical manufacturing processes.

2. Data Acquisition Capabilities

The pilot unit must include provisions for detailed monitoring of process temperatures and pressures and for collection of representative gas samples from the waste gas source, from the inlet and outlet of the burner section and from the outlet of the combustion chamber or stack. The collected data should permit calculation of gas flow rates, mass emission rates, heat and material balances and permit the assessment of the effects of changes in gas mixing, combustion temperatures and residence time. The provisions for gas sampling should include access ports for sampling and measuring the following: particulates, total hydrocarbon by flame ionization detection, specific organic component analysis by gas chromatograph, O_2, CO_2, NO_x, HCl, CO, SO_2, and H_2O.

3. Pilot Unit Duty Requirements

The pilot unit should meet the following duty requirements:

a. Waste gas flow of 1000 scfm with capability for turndown to about 250 scfm.

b. Dilution of waste gas for VOC concentration and O_2 adjustment.

c. Controlled preheating of waste gas to 700°F by exchange with hot combustion gases.

d. Natural gas firing with provision for future addition of fuel oil firing components.

e. Variable conditions for mixing of waste gas with combustion gases from auxiliary fuel.

f. Combustion temperature range of 1200-2200°F.

g. Residence time range of ¼-1 sec at 1400°F by varying gas flow rate. Option of increasing residence time range to 1-2 sec by increasing size of combustion chamber.

h. Dilution cooling of hot combustion gases to 1400°F as required to protect recuperative heat exchanger.

i. Removal of acid gases or SO_2 when potential exists for harmful concentrations in work environment.

j. Dispersion of combustion gases for worker protection.

4. Transportability

The pilot unit should be constructed on three skid-frame sections: a thermal oxidizer module, a heat exchanger module with all interconnecting ductwork and the stack, and a scrubber system module (if required). Depending on arrangement of components, the size of the oxidizer module is estimated to range from about 5 to 9 ft wide by 15 to 17 ft long and weigh from about 4000 to 5000 lb. The size of the heat exchanger module can range from about 7 to 12 ft wide and 12 to 21 ft long and weigh from about 2000 to 3000 lb. An acid gas scrubber module is estimated be about 3 ft wide by 6 ft long by 12 ft high and weigh about 1000 lb. Total estimated weight is 7,000-10,000 lb. The modules should be shipped by flat-bed truck with loading and off-loading accomplished by fork truck or overhead crane. Design for permanent installation on a flat-bed trailer is a potential option.

5. Equipment Availability

a. Existing designs for small incinerators will not meet the wide range in duty requirements outlined for the pilot thermal oxidizer.

Existing incinerator designs offer limited ability for controlled variation of waste gas-combustion gas mixing, gas flow rate or residence time.

b. Most thermal oxidizers are designed to meet the special requirements of a specific application. However, existing equipment components can be relatively easily adapted for use in a pilot equipment system.

6. Pilot Unit Estimated Cost

a. A budget-type cost estimate for purchase of the pilot unit system including the thermal oxidation module and the heat exchanger module is $114,000. The estimated additional cost for a acid gas scrubber system module is $50,000.

b. The above costs of a system designed specifically for pilot service are approximately 50% higher than for a "standard" incinerator of existing design.

7. Manpower and Utility Estimates

a. Conducting a pilot incinerator emissions test is estimated to require approximately 4 people including a test program manager, an incinerator operator and 2 sampling and analytical personnel.

b. The pilot unit will require 110 volt/1ϕ/60 Hz, 2-4 kw and 220/440/3ϕ/60 Hz, 3-6 kw. Average/maximum natural gas useage is estimated to be 250/1700 CFH. A scrubber, if required, will use 15 to 20 gpm of water.

C. RECOMMENDATION

The pilot system should be a unit designed specifically for the purpose of obtaining field performance data on which to base the design of larger scale units. The thermal oxidation process should be designed and specified in detail, using the preliminary requirements developed in this report as design bases. A fabrication bid package should be issued to qualified vendors requesting purchase and/or lease price options.

D. DESIGN BASES

1. VOC Waste Gas Characteristics

The characteristics of waste gases considered for control by thermal oxidation are almost as varied as the number and types of VOC compounds emitted from industrial processes. Processes involving solvent evaporation (metal degreasing, printing, dry cleaning, surface coating, etc.), petroleum refining, storage and marketing, and organic chemical manufacture comprise the major sources of VOC emissions. The waste gas streams from these sources can be composed of VOC only, mixtures of VOCs and air, or inert gases containing low to high concentrations of VOC. The oxygen content of some of the VOC-in-air streams are insufficient to support combustion. The composition of the VOCs can range from compounds containing carbon and hydrogen only to hydrocarbon compounds which can contain one or more of the following elements: oxygen, nitrogen, sulfur, halogens (primarily chlorine), or phosphorous.

Because virtually all VOC compounds can be controlled by thermal oxidation, the identification of specific or typical compounds is not necessary for the design of a pilot control system. Instead, the projected ranges in waste gas characteristics are outlined below to provide a basis for defining duty requirements for the pilot incinerator.

a. VOC Composition -- For the purpose of this study, VOC compositions are based on the average composition of 219 organic compounds previously surveyed for an EPA control device evaluation report on thermal oxidation (5). VOC compounds are represented by the elemental compositions of 68.3% C, 11.4% H and 20.3% O. Halogen-containing VOC compounds are represented by 34.3% C, 4.7% H and 60.6% Cl. Chlorine is selected to represent halogenated VOC's because it is more commonly found in waste gas streams and represents a realistic halogen duty requirement for the system. The chlorine fraction can range from 31.5 to 92.2%.

b. Heat Content -- The heat content of the organics in the process waste streams can vary from negligible to over 150 Btu/scf. However, because

industrial insurers require organic concentrations to be maintained below 25% or 40% of the lower explosive limit (LEL), most waste streams will contain less than 13 Btu/scf or 20 Btu/scf in air, respectively.

c. Oxygen Content -- Because VOC waste gases are vented directly from manufacturing processes as pure compounds, in inert gas carriers or in air streams, the level of oxygen can vary from 0% to about 23% by weight in air.

d. Moisture Content -- Dilute VOC waste streams resulting from the evaporation of organic solvents will approach the levels of moisture present in ambient air. Concentrated VOC waste gases and essentially inert waste gas streams may contain little or no moisture. However, these latter streams will frequently be diluted with ambient air to reduce the level of flammability or to provide oxygen for combustion, resulting in the addition of moisture to the stream. For design purposes, a maximum moisture level of 6.5 mole % by volume (about 0.043 lb moisture/lb dry air) is recommended.(6)

e. Particulates -- Solid and/or liquid particulates are present in many industrial waste gas streams. The particulates may be process materials other than VOC's. The sources of solid particulates include: ambient air supplied to the process, aerosols of process materials, and the products of incomplete combustion (soot) due to direct-fired heaters in the process. The low concentration of solid particles in most VOC waste streams probably does not have a significant effect on organic destruction performance and is generally well below regulatory requirements for particulate emissions. Even at these low particulate levels however, there is some potential for fouling of fans and heat exchanger equipment.

Liquid particulates however can have a significant effect on thermal oxidation performance and their potential presence should be considered in pilot unit design. The sources of liquid particulates include aerosolization of process materials and condensation of high molecular

weight compounds upon cooling in the VOC generating process or in exhaust ducts. The size of the liquid particles is believed to generally be <1 μm. The concentrations that might be experienced is difficult to estimate, but should be less than 0.1 grain/scf for most waste streams. There is some potential for fouling of ductwork, fans and heat exchange equipment if significant concentrations of particulates are present.

For proper definition of pilot unit operating conditions and scale-up data, it is very important that the concentration of solid and or liquid particulates in the process stream be determined by sampling and analysis both prior to and during field test operation of the unit.

2. Critical Process Parameters

The effective oxidation of organic gases depends on the following process parameters:

Waste gas characteristics
Mixing of waste gas and combustion gas from auxiliary fuel
Combustion gas temperature
Combustion gas residence time

In full scale industrial applications, only combustion temperature is variable over a wide range. Gas mixing and residence time are essentially fixed by the burner and combustion chamber geometry and the waste gas flow rate. In a pilot plant application for acquiring data on emission control performance and for scale-up of process size, it is desirable to be able to vary each of the parameters and to measure the effect of such changes on system performance. The importance of the parameters and suggested operating ranges are discussed below.

a. Waste Gas Characteristics -- For operating safety and to meet industrial insurance safety requirements, the concentration of organics should not exceed 25% (or in special cases, 40%) of the lower explosive limit (LEL). Additionally, for oxygen deficient streams, the concentration of oxygen should be increased to about 16% or more for adequate combustion. These conditions are normally controlled by the upstream addition of ambient air. Inert gas streams or streams containing

organic concentrations above the upper explosive limit (UEL) are usually fed directly to the oxidizer with combustion air being supplied from a separate system.

The waste gas entering the thermal oxidizer combustion chamber should not contain significant amounts of liquid particulates. Depending on particle size, composition and system design, particle evaporation may not take place until well into the combustion chamber, thus reducing the residence time of the vapor at combustion temperature. This can significantly effect thermal oxidizer performance when high organics destruction efficiencies are desired. Preheating the waste gas to volatilize any liquid particulates is strongly recommended to minimize or eliminate this problem.

b. Waste Gas - Combustion Gas Mixing -- Mixing of the waste gas with the hot gases from the combustion of auxiliary fuel is one of the most important factors in achieving an effective thermal oxidation process. It is the means by which the waste gas is heated to the combustion temperature so that a significant portion of the organics are oxidized. Effective mixing provides uniform combustion gas temperatures, increased time at temperature and increased reaction of organics with free radicals which are present in significant amounts only within the flame region.

Effective gas mixing is usually accomplished by passing a portion of waste gas through the burner and by creating turbulent flow conditions at the flame front with the balance of gas flow. Gas velocities in the range of 25-50 fps are used to insure turbulence.(7) Design for proper mixing over a range of burner firing rates and gas flow rates is important because excessive turbulence within the flame zone can result in cooling or quenching of the flame and non-uniform temperatures or gas compositions in the combustion chamber.

Because numerous types of burners are used in a wide variety of combustion chamber designs to achieve mixing, it is difficult to identify a

specific design for a pilot unit which would be representative of all commercial thermal oxidation units. However, since all burner sections should be designed to achieve uniformity of gas conditions at the outlet of the mixing section, a uniform gas temperature profile at this point should be a good measure of mixing effectiveness and a recommended performance requirement. Because oxidation of organics is very temperature sensitive and because large disparities in gas temperature tend to carry through the combustion gas retention section, the temperature of the heated mixed gases at any point in the outlet of the mixing section should be within roughly 50°F of the average gas temperature. Other indicators of mixing effectiveness are possible, such as uniformity of gas composition or dimensionless number representations of gas flow turbulence such as Reynold numbers.(8)

If possible, the pilot unit should have provisions for varying mixing effectiveness while holding retention time or temperature constant and vice versa. To accomplish this, the burner assembly should be adjustable to maintain turbulent mixing conditions at low waste gas flow rates. For example if burner geometry is fixed, a large decrease (say 4:1) in waste gas flow to increase combustion gas retention time will also decrease gas mixing at the flame front, which may offset any increase in organic destruction achieved due to the longer retention time. Adjustment of burner-to-burner chamber geometry to maintain a high degree of mixing will enhance measurement of the effects of other critical design parameters.

c. Combustion Gas Temperature -- Because of the potentially wide range in VOC waste characteristics, the pilot thermal oxidizer must be capable of operating at temperatures ranging from 1200°F to 2200°F. Typical operation is anticipated to be on dilute VOC streams (heat content <13 Btu/scf) at temperatures of about 1400°F ±100°F. Tests involving concentrated VOC are possible and could require operation at temperatures up to 2200°F as a result of stream heat contents up to 50 Btu/scf. For halogenated waste streams, the pilot unit should be capable of operating up to 2200°F to maximize the formation of hydrogen halides such as HCl (acid gas) which are more easily removed from the flue gas stream than the free halogen gases such as chlorine.

The high combustion temperature capability will also permit the pilot unit to be used for experimental applications other than VOC control. For example, it could be used to assess the potential for disposal of waste organic liquids in a fume incinerator and in research studies on the destruction of thermally stable, non-VOC gases.

d. Combustion Gas Residence Time -- It has long been established that residence time is an important factor in determining destruction efficiency.(7) When the cost of energy was low compared to equipment cost, residence times (combustion chamber size) were minimized to reduce capital cost because satisfactory destruction efficiencies could be achieved by operating at higher combustion temperatures with increased fuel consumption at relatively low cost. With the present rapidly increasing cost of energy, it is important to consider increasing residence time to permit operation at lower combustion temperatures. This consideration is based in part on an EPA control device evaluation report which indicates that increases in residence time from 0.5 to 0.75 sec. have little effect on equipment costs.(5) It is therefore important that the pilot unit be capable of operating over a wide range of residence times and combustion temperatures to provide data for determination of cost-effective operating conditions.

There are limitations in a pilot-scale system, however, as to how much flexibility can be provided and still remain representative of full-scale commercial designs. For example, most commercial units for the control of dilute hydrocarbon fumes are designed for hot (~1400°F) gas velocities of 20-40 fps.(7) If a combustion chamber length of about 10 ft is selected as a practical maximum for handling and transportability, then the residence time range will be only 0.25 to 0.50 sec. with gas velocities in the usual range. Increasing combustion chamber length to increase residence time to 1 sec. or 2 sec. is not recommended because excessive lengths (40-80 ft) would be required and also because heat loss from the surface of a long, narrow combustion chamber will be a significant part of burner duty and both conditions are not representative of a full scale unit. Therefore, the only feasible

alternative is to accept a reduction in the usual hot gas design velocities by reducing volume flow rate or increasing chamber diameter. This should be a reasonable alternative, because if gases are uniformly heated and mixed in the burner section, the need for high velocities through the combustion chamber to further mix the gases should be reduced. With proper premixing, gas velocities below 20 fps and down to 5 fps may be acceptable. The capability of operating at a gas velocity of 40 fps and at 1400°F should be retained so that comparative data can be acquired.

For a given pilot system size, there is a limit as to how far waste gas flow can be reduced to vary residence time. A 4:1 reduction in waste gas flow is considered the feasible maximum. For a 10-ft long chamber, this will give a residence time range of 0.25-1.0 sec at gas velocities ranging from 10-40 fps at the 1400°F operating temperature. Residence time will also vary in direct proportion to changes in temperature. These conditions are recommended for the pilot system design as covering the range of operation of most commercial incineration systems operating on dilute hydrocarbons.

For residence times in excess of 1 sec, it is recommended that the pilot unit be provided with a separate (interchangeable) combustion chamber of the same length but of larger diameter (or width and height). This chamber should be designed for residence times of at least 2 sec while operating at combustion temperature of 2200°F.

e. Oxidizer Emissions -- For VOC waste streams containing primarily hydrocarbons in air, the oxidizer exhaust gases will contain relatively low concentrations of carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (unreacted VOC and intermediate reaction products), and possibly solid particulates. Normally, the small amounts of these air pollutants can be dispersed to atmosphere without significant deterioration of ambient air quality as required by the National Primary and Secondary Ambient Air Standards (40 CFR, Part 50) of the Clean Air Act. It is therefore assumed that additional controls in the form of

scrubbers or filters will also not be required for the control of these pollutants by the pilot unit.

When halogenated VOC or sulfur-containing VOC are oxidized, the combustion gases will contain free halogen gases (Cl_2, Br_2,), acid gases (HCl, HBr, HF) or SO_2 in concentrations ranging from <100 ppm to several thousand ppm. Since the maximum concentrations allowed by OSHA for (time-weighted) exposure to these compounds range from only 0.1-5 ppm, the emissions from the pilot unit must be controlled and/or effectively dispersed to avoid a potential human health hazard for the pilot unit operators and other workers in the test site area.

Because chlorinated VOC are much more common than other halogenated compounds and to simplify design, it is recommended that the pilot system be designed only for the control of HCl acid gases. Based on presently available information, HCl emissions should be controlled by liquid scrubbing of the flue gas. An HCl scrubbing system may be adaptable for removal of SO_2 or HF or bromine forms (Br_2, HBr) if the need occurs. These latter conditions however require considerable additional evaluation for definition of detail design requirements.

3. Other Scale-Up Considerations

The pilot unit should be capable of operating over a wide range of conditions that will permit the acquisition of data for optimizing process conditions and be representative of full-scale equipment systems. Several critical process parameters were discussed in the previous section. Other factors such as typical physical characteristics of commercial equipment should also be taken into consideration in selection of pilot system design criteria.

a. Typical Capacity and Sizes -- While commercial thermal oxidizers range in capacity from about 300-100,000 scfm, available information indicates that most units have capacities in the 4,000-40,000 scfm range. Typical combustion chambers sizes are estimated to range from about 2-10 ft in diameter (or equivalent rectangular dimensions) and from

6-30 ft long. The ratio of combustion chamber length to diameter ranges from 2-6, but 3-5 is more typical.(7) The L/D for the recommended pilot unit is 7.5 for the .25-1 sec combustion chamber and 5.0 for the 1-2 sec chamber.

b. Configuration -- With increasing use of heat recovery equipment, many thermal oxidizer systems are being designed with one or two 90° turns in the combustion chamber. The "L" or "U" shapes conserve space (and reduce cost) by allowing compact design and also protect the heat exchanger surfaces from exposure to radiant heat from the burner flame. The "U" configuration however causes the gas flow to be non-uniform and creates stagnant areas, conditions which have the effect of reducing the average gas residence time. Baffles are sometimes added to these types of chambers to improve the uniformity of gas flow and temperature. These configurations also tend to increase system pressure drop.

Because these increasingly common configurations tend to decrease system performance over a straight combustion chamber which gives "plug-flow" (gas moves as a plug at uniform velocity and temperature), it is recommended that the "L" or "U" shape be considered as a design feature of the pilot unit.

In small thermal oxidation systems, as in pilot systems, the geometry of the components have the potential for affecting destruction performance. For example, the interior surface area (A) to volume (V) ratio increases rapidly as small combustion chambers fall below 2 ft in diameter. For chamber diameters of 0.5, 2, 5 and 10 ft, A/V equals 8, 2, 0.8 and 0.4, respectively. When the interior surface area is much larger than the volume (say A/V>2), there may be a significant potential for the chamber walls to have a large effect on gas mixing and gas cooling resulting in performance that is not representative of a full-sized incineration system.

Probably a more important consideration is the effect that geometry has on surface heat losses. Surface heat losses from commercial units are

estimated to be about 2-3% of the burner capacity. In small units (0.5-2 ft), heat losses potentially can range from 3% to over 25% unless special precautions are taken to minimize the losses. The heat losses in a small unit mean that the burner will have to fire at a proportionately higher rate than in a larger unit, which may tend to improve oxidation performance. Excessive surface heat losses may also cause the temperature of hot gases to decrease as they pass through the combustion chamber. The pilot system should be designed to minimize the effect that surface heat losses have on burner firing rate and combustion temperature.

c. Scale-Up Factors -- Based on a limited review of available information and vendor discussions, pilot thermal oxidation systems appear to fall into two size ranges, <100 scfm and 1000-3000 scfm. Design scale-up factors for the smaller pilot systems can range up to 800:1, while the factors for the larger pilot systems range up to only 40:1. The small units are particularly useful for experimental work on reaction kinetics, compound thermal stability and identification of ideal temperature and time requirements for destruction of organics. The small systems are often electrically heated thereby eliminating exposure to free radicals as a positive factor in the oxidation process. Frequently, the provisions for mixing the waste gases with the hot combustion gases are not representative of full-scale processes. The smaller units should probably be referred to as laboratory or bench-scale systems rather than pilot scale.

The larger pilot systems (1000-3000 scfm) are usually small size production designs which are used to obtain data for the optimum design of a much larger unit. The lower limit of practical pilot unit size appears to be about 250 scfm, which is determined by available burner sizes, burner-chamber geometry, and heat loss factors. If a 4:1 turndown of gas flow is desired to investigate the effect of changes in residence time, then a unit size of 1000 scfm is recommended as the minimum capacity for a pilot unit.

4. Safety Requirements

A pilot incinerator for temporary installation at several test sites must not only meet national standards and codes for fuel burning equipment but also any safety regulations or codes required by local government agencies or the host plant's safety department. While it is impractical to try to identify all possible safety requirements, the majority can be satisfied by following the codes, standards and recommended practices published by the National Fire Protection Association (NFPA). Official approval of system design by NFPA will satisfy most local codes. It should be anticipated however, that a formal review and approval may be required by the owner's safety department and/or the industrial insurance underwriter for each plant site. Detailed piping and instrument drawings must be prepared and maintained current for safety review purposes. Inspection of the installed system by owner and operator representatives prior to start-up should be mandatory.

Due to the cyclical nature of many process operations or to process upsets, the concentration of VOC in waste gas streams can vary from dilute to very concentrated; as a result, concentrations may be in the combustible range for a period of time. For this reason and because pilot unit operators may not be familiar with process variabilities, it is recommended that the concentration of combustible gases in the waste stream be continuously monitored with the capability for automatic shut-off of waste gas flow and purging with ambient air.

Some potential test sites may be in plant areas where explosion-proof equipment construction is required. A recommended procedure is to duct the gases to a safe area where standard materials and procedures can be applied. The operation of a pilot thermal oxidizer in hazardous areas is not recommended because the special equipment and procedures required would significantly increase equipment costs, testing program costs and the risk of worker injury and property loss. Special sampling equipment and analytical procedures would also be required in such an environment. Explosion-proof construction is not considered necessary or advisable for the pilot unit.

5. Process Condition Measurements

Considerably more data on process temperatures, gas flows, pressure drops, and gas composition should be collected from a pilot unit than is normally provided for in a full-scale unit. The data is important for assessing the effect that changes in critical design parameters have on system performance. The collected data should not only permit definition of effective process conditions but also calculation of confirmatory heat and material balances and assessment of performance of individual equipment components.

The process measurements recommended for the various gas streams in the pilot unit are identified in Table III-1. The table is intended only to indicate that provisions for taking the measurements be included in the design of the pilot unit. For example, a temperature indicating recorder-controller is recommended for combustion temperature while sampling ports are all that is necessary for the flow rate and gas composition measurements. The actual measurements will be part of an associated sampling and analytical program. The decisions as to which process conditions should be automatically indicated, controlled and recorded, indicated only, or obtained by utilizing portable instruments at sample ports are considered part of the detail design and beyond the scope of this project.

The sampling ports for the waste VOC streams and the stack gases should be sized to permit sampling for particulates by EPA method 5. Sampling ports for measurement of gas velocity and determination of flow rates should be designed for use of EPA method 2. Sampling ports for collection of hot combustion gas samples should be sized for the special probes required to withstand the high temperatures.

6. Transportability

The pilot system should be of single unit or modular component construction that can be transported by trailer or shipped by commercial truck carrier. The system unit or its components should be steel frame skid-mounted for easy handling at test sites. It is assumed that the

Table III-1. Recommended Process Measurements for a Pilot Thermal Oxidation System

	Temperature	Pressure	Flow Rate	Gas Composition
Waste VOC stream				
Source gas	X		X	X
Heat exchanger inlet	X	X		
Burner section inlet	X	X		X[a]
Combustion gas stream				
Burner section outlet	X	X		X[a]
Combustion chamber	X			
Combustion chamber outlet	X	X		X[a]
Heat exchanger inlet	X	X		
Heat exchanger outlet (stack)	X	X	X	X
Ambient air streams				
Waste gas dilution	X		X	X[b]
Combustion air	X		X	X[b]
Combustion gas quench	X		X	X[b]
Auxiliary fuel				
Natural gas			X	
Fuel oil (if included)			X	

[a] Necessary only for specific operating conditions.

[b] Moisture content only.

unit will be operated at ground or floor level with loading and off-loading by fork truck or overhead crane. Permanent installation on a flat-bed or low-boy trailer can also be considered during detail design phase.

The maximum weight of any single component should not exceed 6000 lb to remain within the load-carrying capacity of a large fork truck. For shipping convenience, the maximum dimensions of the unit or any component should be less than 8 ft wide by 10 to 15 ft long by 6 to 8 ft high. Although there is no limit on the size of an assembled modular pilot system, it should be kept as small as possible to minimize cost and handling problems. Overall road height for trailer and pilot unit must not exceed 13 ft 6 in. Normal over-the-road width of 8 ft 0 in. is desirable, but transportation of 10'0" wide loads is possible although special permits may be required in some states. An overall weight limit of 18,000 lb per axle is believed to be acceptable in all states. (The total weight of the pilot system with scrubber is roughly estimated to be 7,000-10,000 lb.)

The individual components and the assembly must be designed to withstand the vibrations and shock of highway transport and the stresses of loading and off-loading.

7. Assembly and Operating Considerations

The pilot system should be designed for easy assembly and connection to local utility services. It is assumed that the unit will be assembled under the direction of a pilot system operator with assistance as required from local tradesmen such as millwrights, electricians, and pipefitters.

It is anticipated that the unit will be used at any one test site for periods ranging from 1 week up to 3 months. While provision for continuous operation should be included, each experimental test is expected to be completed within 8 hours.

The unit should be designed for manual start-up and shut-down and automatic operation by a single experienced operator. All waste gas, dilution air, quench air and combustion air flows and the preheat temperature will be set manually. Only the combustion temperature will be automatically controlled. Instruments and controls will be provided for automatic shutdown in case of overtemperature or loss of air or waste-gas flows. It is assumed that the overall operation of the pilot system will be under the direction of a test program manager.

The sampling and analytical program for determining system performance is beyond the scope of this project. It is anticipated however that this program will require a minimum of two people who will operate out of a mobile laboratory specially equipped for the purpose.

E. PRELIMINARY PROCESS DESIGN

1. Process Description

A block process flow diagram for the pilot thermal oxidation system is shown on Fig. III-1. The diagram illustrates the major system components that will be required to meet the full range of capabilities previously described in the design bases. The combustion gas quench and scrubber system is shown in dashed lines to emphasize that it would be installed in the system only when the waste gases contain halogens or sulfur.

As shown on the process flow diagram, 250 to 1000 scfm of waste gas at 100°F is drawn from a VOC source, with the flow rate being determined by a manually set volume control damper. If the concentration of organic in the waste gas in less than 25% LEL (40% LEL if concentration is monitored by an approved safety system) and contains sufficient oxygen for complete combustion, the waste gas is forwarded by fan through a high gas velocity section of duct (flame flashback preventer) to the recuperative shell and tube heat exchanger where it is heated to a maximum of 700°F by indirect exchange with the hot combustion gases.

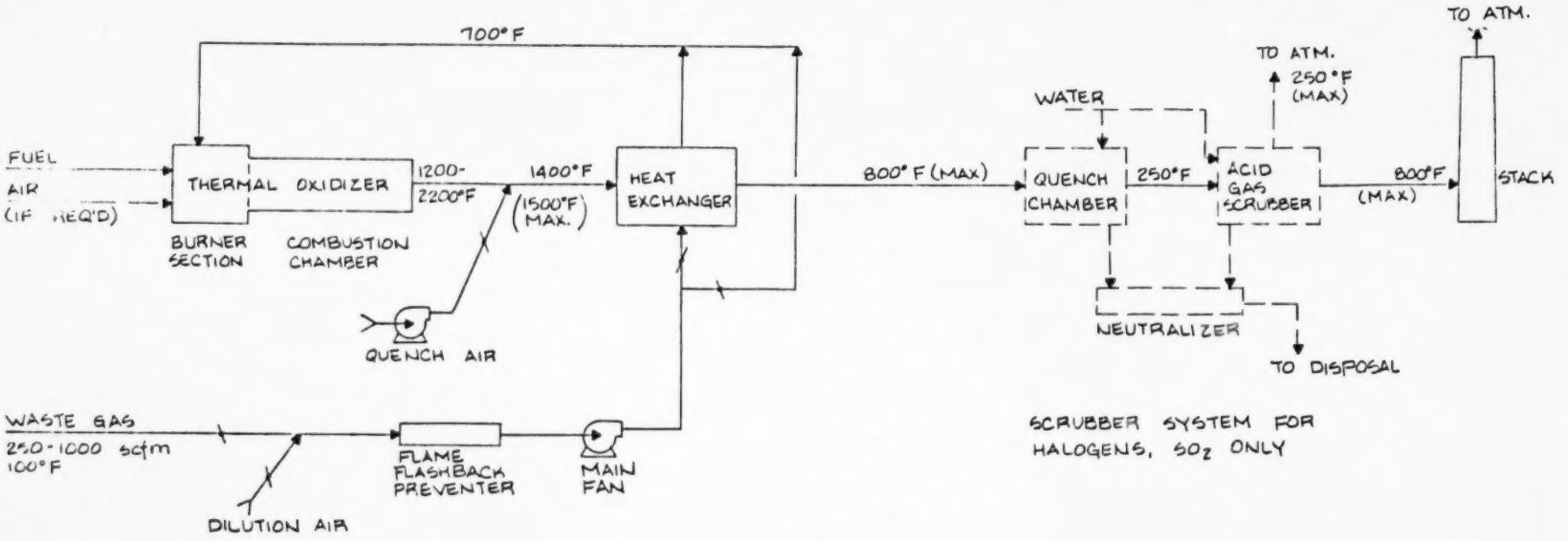


Fig. III-1. Preliminary Process Flow Diagram for Pilot VOC Thermal Oxidation Unit

If the concentration of organics in the waste gas exceeds 25% (or 40%) LEL, or if the gas is oxygen deficient, then ambient air can be drawn in to dilute the organics or increase the oxygen content with the amount being determined by manually setting the volume control damper. The waste gas and ambient air mixture is then forwarded to the heat exchanger as described above. The volumetric flow rate of the mixture should not exceed 1000 scfm.

The waste gas volume control damper should automatically close and the dilution air damper automatically open upon shut-down of the thermal oxidation system for any reason. This action should also occur if the concentration of the VOC reaches the combustible range at the inlet to the main blower.

For waste gas heat contents >13 Btu/scf, it may be necessary to preheat to temperatures lower than 700°F because of the temperature increase due to the combustion of the organics and the minimum fire auxiliary fuel. The preheat temperature can be controlled by by-passing a portion of the waste gas around the heat exchanger as shown in the figure.

The preheated waste gas then flows to the burner section of the thermal oxidizer, where a portion is supplied to the auxiliary fuel burner for a source of oxygen and the balance bypasses the burner to mix with the hot combustion gases under turbulent conditions in the flame zone. The waste gases are heated to combustion temperatures by mixing with the hot combustion gases generated in the burner by oxidation of the auxiliary fuel and a portion of the waste organics.

The oxidation of the waste organics continues as the combustion gases flow through the combustion chamber for time periods varying from about ¼ to 1 sec, depending on the gas flow rate. The temperature of the gases in the combustion chamber are measured by thermocouple and automatically controlled by adjusting the flow of fuel through the supply valve.

At combustion temperatures <1400°F, the gases then pass through the recuperative heat exchanger where they are cooled to less than 800°F, and then through the stack to the atmosphere. To protect the heat exchanger and the stack from temperatures in excess of 1400°F and 800°F respectively, combustion gases with a temperature >1400°F will be cooled by mixing with up to 1000 scfm of ambient air supplied by a quench air fan as shown.

When the waste gases contain chlorinated hydrocarbons, an acid gas scrubbing system will be installed in the pilot system with combustion gases first being cooled to <250°F by water spray in a quench chamber then contacted with once through water in a scrubber section for absorption of HCl. The gases exiting the scrubber pass through a mist eliminator prior to discharge through the stack. The water drained from the quench and scrubber will be neutralized to a pH of greater than 5 prior to discharge to a sewer system.

2. Equipment List

The major components of the pilot incinerator are listed below. When available, estimates of capacity, size, weight are also listed to briefly describe the equipment.

a. Inlet Duct Section——Waste gas volume control damper (0—1000 scfm), dilution air volume control damper (0—500 scfm), venturi (flame flashback preventer). (Insulation is not required for gas design temperature of 100°F. If gas temperatures >140°F are encountered, insulation or heat shields can be provided at that time for personnel protection.) Weight estimated at <200 lb.

b. Main Supply Blower——1000 scfm capacity at estimated 12 to 16 in. W.C. pressure and at maximum operating temperature of 400°F. Belt driven with adjustable sheaves and shaft seals. Motor horsepower is roughly estimated at 3 to 5 HP range. Weight estimated at ~150 lb.

c. Recuperative Heat Exchanger——Shell and tube type; ∿0.7 MM Btu/hr capacity; waste gases tube side (100 to 700°F) and flue gases shell side (1400 to 800°F). Stainless steel tube and mild steel shell construction required. Include by-pass ductwork and two flow control dampers. Components insulated to maintain surface temperatures <140°F. Weight is estimated in 500 to 800 lb range.

d. Thermal Oxidizer-Burner Section——Consists of waste gas flow chamber (outside) and burner assembly (inside). Burner assembly includes fume bypass controls, natural gas burner, and refractory (2800°F) lined flame or ignition tube. Position of burner components adjustable for control of waste gas bypass and gas mixing at flame front. Burner assembly to have provisions for future firing of fuel oil and for separate supply of combustion air to burner. The inside diameter of the outer chamber should be ∿2 ft to allow for a representative burner size. The outlet of the burner section should be restricted to about 1'4" in diameter to allow for connection to a smaller diameter (cross-section) combustion chamber and to improve mixing of waste gas with combustion gases of the auxiliary fuel. Burner heating capacity is estimated at 0.4MM Btu/hr and 1.7 MM Btu/hr when operating at 1400°F and 2200°F respectively. Weight of burner section is estimated at 700 to 1000 lb.

e. Thermal Oxidizer-Combustion Section——Mild steel chamber lined inside with at least 2200°F lightweight castable refractory; approximate dimensions 1 ft 4 in. I.D. X 10 ft long. Refractory and outside insulation to minimize surface heat losses (<5% of burner output at the maximum firing rate at 1600°F) and to protect personnel from hot surfaces. Optional: a second interchangeable combustion chamber of approximately 2 ft I.D. X 10 ft long for residence times of 1 to 2 sec. Estimated weight of each chamber is 2000 to 3000 lb and 3000 to 4000 lb respectively.

f. Quench Air System——Forced draft fan ductwork and volume damper with an estimated capacity of 1000 scfm at 100°F and 4 to 8 in. W.C. Includes refractory lined chamber section for mixing of hot and cold gases.

g. Acid Gas Scrubber System——Optional, modular unit for installation in place of stack and consisting of water spray quench chamber, counter-current packed scrubber and acid neutralization tank. The unit should be constructed of fiberglass reinforced plastic to resist corrosion. Approximately 1300 acfm capacity with estimated pressure drop of 2 to 3 in. W.C. Water use rate is estimated at 15 to 20 gpm. Estimated weight of skid-mounted module with short stack is approximately 1000 lb.

h. Stack——Mild steel pipe approximately 1 ft in diameter. Minimum length is estimated at 15 ft; actual length to be determined by gas dispersion or site requirements. Insulation or heat shields for personnel protection. Detachable for installation of scrubber.

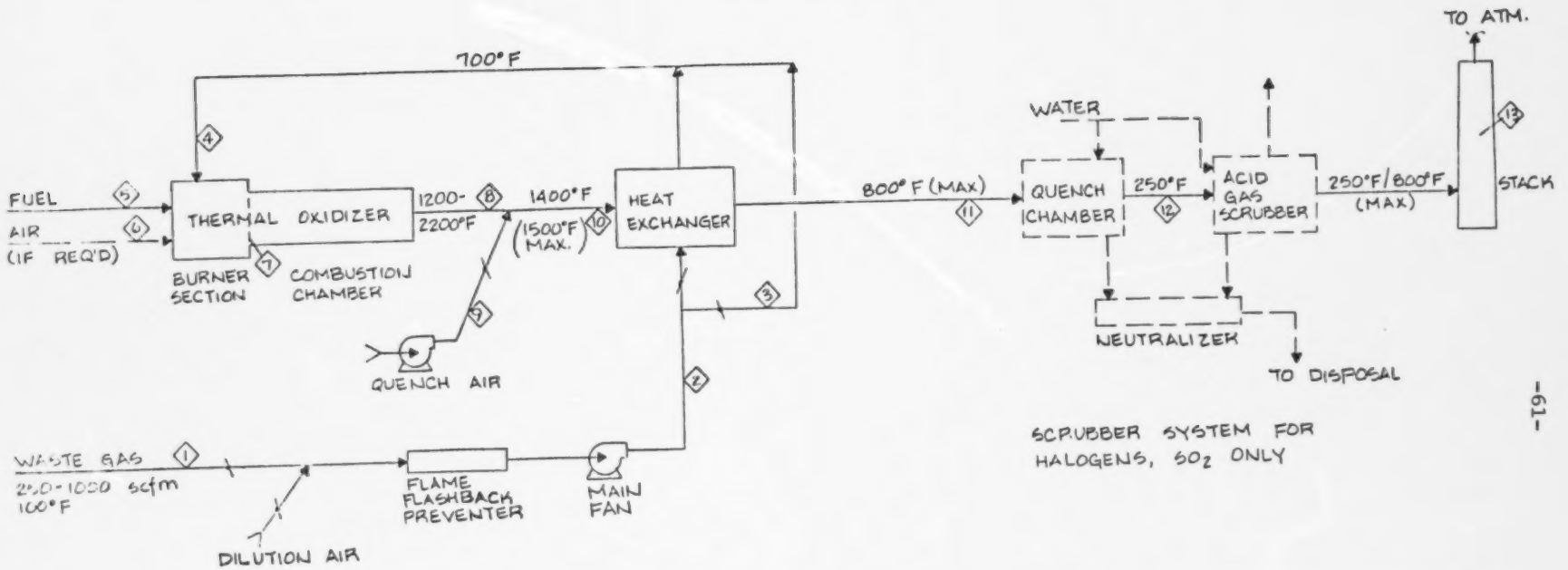
3. Instruments and Controls

The locations for process measurements and sampling points are shown on Fig. III-2. The major components are listed below.

a. Fuel Supply Valve Trains——For main natural gas burner: main valve, pressure regulator, pressure indicator, pressure low switch and alarm, solenoid block valve (upstream), vent pipe with solenoid valve, solenoid block valve (downstream), pressure high switch alarm, automatic flow control valve with activator and flow measurement device.

b. Process Control Instruments——Flame safeguard system; combustion temperature; high temperature limits on gases in combustion chamber at the inlet to heat exchanger and the inlet to the scrubber system; high and low natural gas pressure; low waste gas pressure (flow) at inlet to burner section. Combustion gas analyzer with automatic shut-off of waste gas flow and opening of dilution air valve upon oxidizer shut-down. Automatic control of gas temperature entering heat exchanger.

c. Process Monitoring Instruments——Temperature: waste gas inlet, heat exchanger inlet, burner section inlet and outlet, combustion chamber outlet, heat exchanger inlet and outlet, quench chamber outlet, and



	1	2	3	4	5	6	7	8	9	10	11	12	13
TEMPERATURE	x	x		x			x	x	x		x	x	x
PRESSURE	x	x		x			x	x		x	x		
FLOW RATE		x	x		x	x			x				x
SAMPLE PORTS	x	x					x	x					x

Fig. III-2. Recommended Locations for Measurement of Process Conditions - Pilot VOC Thermal Oxidation Unit

stack. Pressure: main fan outlet and scrubber inlet and outlet. Other measurements obtained manually with portable instrument at sample ports. Temperature recording requirements to be defined during detail design.

4. General Construction Guidelines

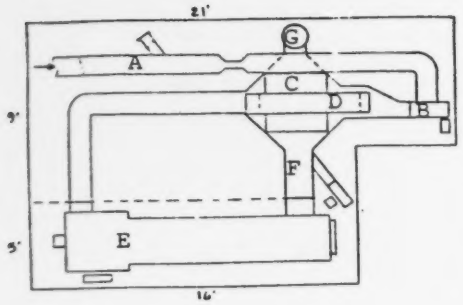
General requirements for design for transportation were previously discussed in paragraph D.6. To meet the stresses and vibration of handling and transportation, the pilot system components will be attached to heavy duty steel frame skid of welded construction wherever feasible. Screwed or bolted construction will be designed to resist loosening due to vibration. Shock absorbent mounting may be necessary for some components. Components especially sensitive to damage such as recorders, controllers, combustible gas analyzers, should be demountable for separate shipping in shock absorbent packaging.

Four conceptual arrangements of the pilot unit are shown in Fig. III-3. The arrangements were developed in order to estimate module and unit sizes. Based on these preliminary concepts, the sizes of individual modules are roughly estimated to range from 5 to 10 ft wide by 12 to 21 ft long. Since these sizes are larger than desired (paragraph D.6) for convenient handling by fork truck, the compactness of the modules should be given additional consideration during detail design. Arrangement IV of Fig. III-3 could possibly be permanently mounted on a truck trailer bed if a portion of equipment (blower and inlet ducts) is assembled on-site.

5. Estimated Requirements for Operation

It is assumed that all utilities will be furnished to the pilot unit by the test site owner. Very preliminary estimates of utility requirements are summarized below.

a. Electrical——Control panels and service outlets: 120 V/1ϕ/60 Hz, 2-4 kw. Fan motors: 220/440/3ϕ160 Hz, 4-8 Hp.



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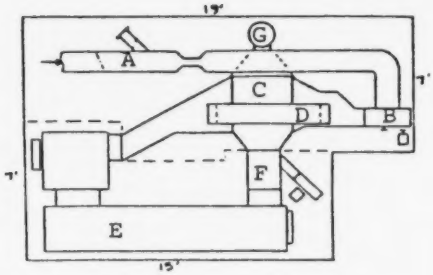
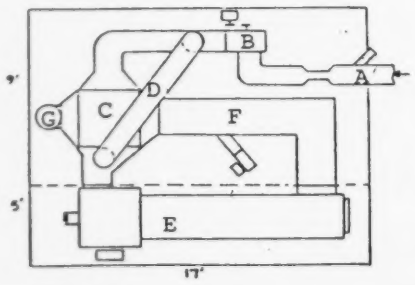
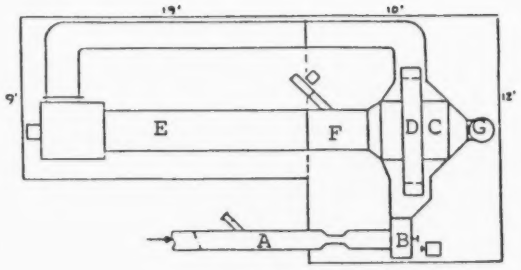


II

A - Inlet duct
B - Main blower
C - Heat exchanger
D - Bypass duct
E - Thermal oxidizer
F - Quench section
G - Stack



III



IV

Fig. III-3. Conceptual Equipment Arrangements
Pilot VOC Thermal Oxidation System

b. Auxiliary Fuel—Natural gas: 1700 CFH maximum, 250 CFH estimated average use. Fuel oil (#2, if used) 12 gph maximum, 1.8 gph estimated average.

c. Compressed Air——For fuel oil firing only: <8 scfm at 100 psig.

d. Water—For scrubber system only: 15 to 20 gpm.

Assembly and connection of the pilot unit should be accomplished by the agency or contractor responsible for conducting the test program. The system should be designed for start-up in about two days elasped time after being set at the test site.

F. COMMERCIALLY AVAILABLE EQUIPMENT

1. Pilot Unit Size

Almost any size of thermal oxidation system is available from manufacturers ranging from <100 scfm laboratory-scale to 3000 scfm full-scale operating units. Typically, each unit is designed for a specific process requirement.

Based on other on-going studies of IT Enviroscience and on discussions with vendors, it is believed important that a pilot unit be of a size, physical configuration and components that are representative of full scale units.(4) Also scale-up ratios of <40:1 would provide considerable more reliability than ratios of 800:1.

For these reasons, a 1000 scfm capacity unit was selected as the minimum size unit for use in acquiring scale-up data.

2. Cost Estimate

Two alternatives were selected for assessment of a cost-effective approach to obtaining scale-up data. The first alternative is to purchase a thermal oxidizer of existing "standard" design which would have limited capability for obtaining scale-up data. The second alternative

is to acquire a thermal oxidation system designed especially for acquisition of a scale-up data and capable of operating over a wide range of test conditions. The budget-type estimates of cost are as follows:

	Standard	Special
Thermal oxidizer	$39,000	$72,000
Heat exchanger	36,000	42,000
	$75,000	$114,000

The cost estimates are based primarily on a small number of budget quotations from vendors and to a limited extent on cost curves previously presented in other EPA documents (5). The "standard" system includes a complete thermal oxidizer (1400-1600°F), recuperative heat exchanger, inlet and bypass ductwork and stack, all mounted on a skid frame. The special design includes the same components, but with special provisions for operation at high temperatures and with halogenated compounds, with complete access for sampling and monitoring, and with the capability of adding an acid gas scrubber if required. An acid gas scrubber is estimated to cost an additional $50,000.

3. Standard vs. Special Design

The factors which are considered important in the selection of a pilot thermal oxidation system are listed in rank order in Table III-2 along with comments on the capabilities or limitations of "standard" or "special" design units.

As indicated in Table III-2, the additional flexibility and capability provided by the special design costs on the order of $39,000 or about 52% more. This cost will probably be small when compared to the cost of manpower for conducting a field testing program which is estimated in the hundreds of thousands of dollars.

Table III-2. Comparison of Factors Considered Important in Selecting a Standard Design or a Special Design for a Pilot Thermal Oxidizer

Factor (Rank Order)	Standard	Special
1. Waste-gas-combustion gas mixing	Conditions fixed or limited to a narrow range of variability.	Can be designed to maintain or increase gas turbulence at flame front with decreasing gas flow.
2. Combustion temperature control	Normally 1400—1600°F maximum	Control to 2200°F.
3. Residence time	Normally about 0.5 sec. with limited variability by gas flow turndown.	Can be designed for 0.25—1 sec, expandable to 1—2 with extra combustion chamber.
4. Waste gas composition	Restricts applications by ~1/3 by eliminating halogenated VOC sources; limited capability for handling wide ranges in waste-gas VOC and O_2 concentrations.	Can handle halogenated VOCs and wide ranges in VOC and O_2.
5. Data acquisition	Very limited instrumentation and access for measurement of process variables.	Can easily be designed for acquisition of data at every process step.
6. Cost	Estimated cost for oxidizer with heat exchanger is $75,000 (7/81).	Oxidizer with heat exchanger estimated at $114,000 add $50,000 for acid gas scrubber.
7. Transportability	Smaller size	Somewhat large size; more complex.
8. Availability	Not a stock item; normally modify existing design to meet project requirements.	Estimate 1-2 months additional bid and delivery time over standard unit.

IV. CATALYTIC OXIDATION PILOT UNIT

A. GENERAL

As with thermal oxidation, the EPA has for several years been investigating catalytic oxidation as part of their overall program for identifying the best available technology for the control of VOC emissions. The investigations include the acquisition of data from laboratory and full-scale operating incinerators, evaluation of destruction efficiency data, and consideration of capital cost and energy use.

One of the problems identified by the investigations is the lack of a well-defined scientific basis for the design of full-scale incinerators. Because of apparatus design limitations and the need to control the number of variables, laboratory-scale systems tend to give idealized performance which is not representative of the more complex operation of a full scale system. There is a need therefore to obtain data which can be used as the bases for design of cost-effective full-scale systems.

The purpose of the pilot catalytic oxidation unit is to provide equipment by which representative process data can be obtained under conditions which approximate or simulate full-scale operation. The pilot unit is intended for investigation of the various process parameters which affect catalytic destruction efficiency and equipment and operating costs.

This report section identifies the preliminary requirements for the detailed design and specification of a pilot catalytic oxidation system with recuperative heat recovery. It includes a discussion of the design bases such as VOC characteristics, critical process parameters, equipment scale-up considerations, safety requirements, transportability and operation. A very preliminary process design is presented in block flowsheet form and the major components are briefly described in equipment and instrument lists. The cost of purchasing a pilot unit is estimated and the applicability of commercially available equipment is discussed.

B. CONCLUSIONS

1. Pilot Unit Applications

Most potential VOC control applications will involve dilute organic concentrations (<13 Btu/scf) in air with sufficient oxygen for combustion. The pilot unit, however, should be designed to handle both dilute emissions as well as high concentration organic waste in oxygen-deficient or inert streams. Because of the special design requirements and limited feasibility, this pilot unit will not be designed for control of waste gases containing significant concentrations of halogens or sulfur. Typical applications include the control of solvents from surface coating operations and emissions from chemical manufacturing processes.

2. Data Acquisition Capabilities

The pilot unit must include provisions for detailed monitoring of process temperatures and pressures and for collection of representative gas samples from the waste gas source, from the inlet and outlet of the burner section and from the outlet of the combustion chamber or stack. The collected data should permit calculation of gas flow rates, mass emission rates, heat and material balances and permit the assessment of the effects of changes in gas mixing, gas preheat temperatures, and catalyst type. The provisions for gas sampling should include access ports for sampling and measuring the following: particulates, total hydrocarbon by flame ionization detection, specific organic component analysis by gas chromatograph, O_2 CO_2, CO, NO_x and H_2O.

3. Pilot Unit Duty Requirements

The pilot unit should meet the following duty requirements:

a. Waste gas flow of 1000 scfm with capability for turndown to about 300 scfm.

b. Air dilution for adjustment of inlet VOC or O_2 concentrations.

c. Initial waste gas preheat to 600°F by indirect exchange with oxidizer flue gas at 1200°F.

d. Final waste gas preheat from 600°F to 1200°F by firing of natural gas. (Normal operating range of 500-1000°F.)

e. Variable conditions for mixing waste gas with combustion gases from auxiliary fuel.

f. Gas velocity range of 15-45 fps at inlet to catalyst bed.

g. Provisions for changing catalyst bed types and bed depths.

h. Maximum gas temperature at catalyst outlet of 1200°F.

4. Transportability

The pilot system should be constructed as a single unit for transport by, and operation from, a flat bed truck trailer. The overall size of the system is roughly estimated at 10' wide by 20' long x 6'8" high (less stack). An optional approach is possibly available, pending further design study, which would involve two skid-frame modules (oxidizer and heat exchanger) transported by commercial carrier, off-loaded and connected at the test site.

5. Equipment Availability

a. Existing designs for small incinerators will not meet the wide range in duty requirements outlined for the pilot catalytic oxidizer. Existing incinerator designs offer limited ability for controlled variation of waste gas-combustion gas mixing, gas flow rate or for changing catalyst beds.

b. Most catalytic oxidizers are designed to meet the requirements of a specific application. However, existing equipment designs can be relatively easily adapted for use in a pilot equipment system.

6. Pilot Unit Estimated Cost

A budget-type cost estimate for purchase of a trailer-mounted pilot unit system including catalytic oxidation and heat exchanger system is $70,000.

7. Manpower and Utility Estimates

a. Conducting a pilot incinerator emissions test is estimated to require approximately 4 people including a test program manager, an incinerator operator and 2 sampling and analytical personnel.

b. The pilot unit will require 110 volt/1ϕ/60 Hz, 2-4 kw and 220/440/3ϕ/60 Hz, 3-6 kw. Average/maximum natural gas useage is estimated to be 150/600 CFH.

C. RECOMMENDATION

It is recommended that the thermal oxidation system be designed for dual use also as a catalytic oxidation unit. With minor modifications for operation with a catalyst bed, the previously described thermal system can meet the duty requirements described in this section as a catalytic oxidation system.

If a separate pilot unit for catalytic oxidation is designed, then it is recommended that the system be designed specifically for the purpose of obtaining field performance data on which to base the design of larger scale units. To assure that the system meets testing requirements, the catalytic oxidation and heat recovery process should be designed and specified in detail, using the preliminary requirements developed in this report as design bases.

D. DESIGN BASES

1. VOC Waste Gas Characteristics

The characteristics of waste gases considered for control by catalytic oxidation are much more narrowly defined than for thermal oxidation. Generally, the waste gases are from processes involving the evaporation of hydrocarbon solvents such as in printing, painting, surface coating, or from organic chemical manufacturing processes such as ethylene oxide, phthalic anhydride, and formaldehyde. The waste gases from these sources can be composed of VOC only, mixtures of VOCs, and air or inert gases containing low or high concentrations of VOC. The oxygen

content of some VOC-in-air streams is insufficient to support combustion. The composition of the VOC compounds will primarily be hydrocarbon compounds containing carbon and hydrogen only or those containing oxygen or nitrogen also. The waste gases should be essentially free of catalyst poisons such as phosphorus, bismith, lead, arsenic, antimony, mercury, iron oxide, tin, zinc, sulfur or halogens.

The projected ranges of waste gas characteristics are outlined below to provide a basis for defining duty requirements for the pilot catalytic oxidizer.

a. VOC Composition——The VOC composition is based on the average composition of 219 organic compounds previously surveyed for an EPA control device evaluation report on thermal oxidation.(5) For the purpose of this study, VOC are represented by the elemental composition of 68.3% C, 11.4% H and 20.3% O. VOC containing halogens are considered a special case not included in the duty requirements for this pilot unit.

b. Heat Content——The heat content of the organics in process waste gas streams can vary from negligible to over 150 Btu/scf. However, because catalyst bed temperatures must be maintained at less than 1200°F, the unit must be designed for a maximum waste organic heat content of about 13 Btu/scf at the inlet to the oxidizer.

c. Oxygen Content——Because VOC waste gases are vented directly from manufacturing processes as pure compounds, in inert gas carriers or in air streams, the level of oxygen can vary from 0% to about 23% by weight in air.

d. Moisture Content——Dilute VOC waste streams resulting from the evaporation of organic solvents will approach the levels of moisture present in ambient air. Concentrated VOC waste gases and essentially inert waste gas streams may contain little or no moisture. However, these latter streams will frequently be diluted with ambient air to reduce the organic heat content or to provide oxygen for combustion, resulting

in the addition of moisture to the stream. For design purposes, a maximum moisture level of 6.5 mole % by volume (about 0.043 lb moisture/lb dry air) is recommended.

e. Particulates- Solid and/or liquid particulates are present in many industrial waste gas streams. The particulates may be process materials other than VOC's. The sources of particulates include: the ambient air supplied to the process, aerosols of process materials, the condensation of high molecular weight compounds upon cooling of the waste gas in exhaust ducts, and the products of incomplete combustion (soot) due to direct-fired heaters in the manufacturing process.

It was not possible within the scope of this study to identify typical concentrations of solid or liquid particulates in VOC waste streams. For the purpose of this study and because filtration can easily be added to the system when required, it is assumed that the concentration of particulates in the waste gases will be negligible.

For proper definition of pilot unit operating conditions and scale-up data, it is very important that the concentration of solid and/or liquid particulates in the process stream be determined by sampling and analysis both prior to and during field test operation of the unit.

2. Critical Process Parameters

The effective oxidation of organic gases by catalytic reaction depends on the following process parameters:

Waste gas characteristics
Waste gas preheating
Gas residence time in catalytic reactor (space velocity)

In full-scale industrial applications, only the preheat temperature is variable over a significant range. Waste gas mixing and reactor residence time are relatively fixed by burner and mixing chamber geometry and the waste gas flow rate. The type of catalyst can be changed; however, it seldom is unless there is a change in waste gas composition.

In a pilot plant application for acquiring data on emission control performance and for scale-up of process size, it is desirable to be able to vary each of the parameters and to measure the effect of such changes on system performance. The importance of the parameters and suggested operating ranges are discussed below.

a. Waste Gas Characteristics——The composition of the waste gas stream has a significant effect on the conditions required for the destruction of waste organics. Compounds vary greatly in the temperature required to initiate catalytic oxidation; for example 300°F is required for carbon monoxide and >900°F is required for methane.

The presence of significant amounts of particulates in a waste stream is frequently detrimental to catalyst oxidation performance.(7) Solid particulates tend to deposit in the catalyst matrix coating the surface or forming chemical bonds with the active sites, both of which inhibit catalyst contact with the waste gas or inactivate the catalyst material. Solid organic particulates are not effectively treated by catalytic oxidation. The presence of liquid particulates is acceptable if the particles can be completely vaporized and the gases mixed prior to entering the catalyst bed.

Sufficient oxygen should normally be present in the waste gas to give an excess of about 3 mole % in the flue gas.(9) Operation with as low as 1 mole % in the flue gas is possible, and is recommended if there is no loss in destruction efficiency. The oxygen concentration of any waste stream without sufficient oxygen should be adjusted by addition of ambient air.

Some waste VOC streams will contain concentrations of combustible gas which exceed the 25% of LEL required for operating safely by industrial insurors. In addition, release of the organic heat contents in excess of about 13 Btu/scf can result in exceeding allowable operating temperature for the catalyst material. These characteristics require design provisions to prevent handling combustible concentrations of gases and

catalyst overtemperatures, usually by dilution of the waste gas with ambient air.

b. Waste Gas Preheating——Depending on the VOC compound, the catalyst type and the destruction efficiency desired, the gas must be preheated to temperatures in the range of 500-1000°F before catalytic oxidation can occur. Heating of the waste gas to these temperatures is accomplished by (1) recovery of heat from the oxidizer flue gas and (2) by the combustion of an auxiliary fuel. If the waste gas has a heat content on the order of 5 Btu/scf or larger, it may be possible, after initial start-up heating, to sustain effective combustion conditions by recovered heat only (no auxiliary fuel heat). Preheating the waste stream also promotes the vaporization of any volatile liquid particulates which might be present and which could potentially be very detrimental to oxidizer performance.

It is recommended that the capability be provided for preheating the waste gases to 600°F by indirect heat exchange with the oxidizer flue gases when flue gas temperatures are at a maximum of 1200°F. Depending on the VOC composition, some thermal decomposition may occur, resulting in partial combustion products which may be either easier or more difficult for a particular catalyst to oxidize. In order to permit assessment of the effects of partial oxidation on destruction efficiency, it is recommended that the pilot unit have provisions to control of recuperative preheat temperatures in the range of 300-600°F. The maximum preheat temperature achievable will of course be reduced when the catalyst bed operates at temperatures lower than 1200°F.

It is very important that the temperature and, to a lesser extent, the VOC concentration of the waste gases entering the catalyst bed be uniform. To achieve this, the waste gas stream must be thoroughly mixed with any dilution air or the hot gases from the combustion of auxiliary fuel prior to entering the catalyst bed. This is accomplished by designing for turbulent flow conditions either at the burner section or in the mixing section, or both. Distributed air burners are used to

spread the waste gas flow over a large grid and to promote uniform heating by turbulent mixing with the hot combustion gases. Burners are designed for gas flow pressure drops ranging from 0.5"-2"w.c.(7) Burner sections which bypass a portion of the waste gas around, rather than go through, the burner for mixing at the flame front are also acceptable. In addition, baffles are sometimes installed downstream of the burner in the mixing chamber to promote further mixing. Gas velocities of at least 25 fps are recommended in the mixing section.(7)

Because numerous types of burners are used in a wide variety of combustion chamber designs to achieve mixing, it is difficult to identify a specific design for a pilot unit which would be representative of all commercial thermal oxidation units. However, since all burner sections should be designed to achieve uniformity of gas conditions at the outlet of the mixing section, a uniform gas temperature profile at this point should be a good measure of mixing effectiveness and a recommended performance requirement. Because oxidation of organics is very temperature sensitive and because large disparities in gas temperature tend to carry through the catalytic reactor, it is recommended that the temperature of the gases at any point in the inlet to the reactor be within about 50°F of the average gas temperature.

If possible, the pilot unit should have provisions for varying mixing effectiveness while holding space velocity or temperature constant and vice versa. To accomplish this, the burner assembly should be adjustable to maintain turbulent mixing conditions at low waste gas flow rates. For example if burner geometry is fixed, a 4:1 turndown of waste gas flow to reduce space velocity will also reduce gas mixing at the flame front which may have a greater effect on organic destruction than the space velocity. Adjustment of burner-burner chamber geometry to maintain a high degree of mixing will enhance measurement of the effects of other critical design parameters.

c. Catalyst Type——Catalysts are specific in the types of reactions they promote.(10) And while there are oxidation catalysts available that

will work on a wide range of organic compounds, it is recommended that catalyst manufacturers be consulted for selection of the best catalyst for general application and for each pilot test. Common catalyst materials include platinum and other noble metals on alumina pellet support or a ceramic honeycomb support. The actual composition of catalyst materials is considered proprietary by most manufacturers.

The pilot unit should be designed to accept a variety of vendor standard catalyst bed configurations and sizes.

d. Gas Residence Time (Space Velocity)——In thermal incineration, the time a waste gas is held at combustion temperature is referred to as residence time. In catalytic incineration, the term space velocity is used to describe the relative time that the waste gas is exposed to the catalyst material. Space velocity is defined as the volume of gas flowing through a catalyst divided by the volume occupied by the catalyst.(11) Space velocities therefore can vary greatly and, like residence time in a thermal incinerator, can have significant effect on organic destruction rates. For the pilot unit, it is recommended that provision be made for testing at space velocities ranging from 30,000 hr^{-1} to 120,000 hr^{-1}.

d. Pilot Unit Emissions——For VOC waste streams containing primarily hydrocarbons in air, the oxidizer exhaust gases will contain relatively low concentrations of carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (unreacted VOC and intermediate reaction products). Normally, the relatively small amounts of air pollutants emitted by a pilot unit can be dispersed to atmosphere without significant deterioration of ambient air quality as required by the National Primary and Secondary Ambient Air Standards (40 CFR, Part 50) of the Clean Air Act and without creating a potential health hazard for pilot unit operators and other workers in the test site area. Some test conditions, however, may result in abnormally high pollutant emissions; therefore, to avoid any potential health hazards it is recommended the pilot unit stack be designed to assure at least a 100-fold dilution of the incinerator flue gases at ground level.

3. Other Scale-Up Considerations

The pilot unit should be capable of operating over a wide range of conditions that will permit the acquisition of data for optimizing process conditions and be representative of full-scale equipment systems. Several critical process parameters were discussed in the previous section. Other factors such as typical physical characteristics of commercial equipment should also be taken into consideration in selection of pilot system design criteria.

a. Typical Capacity and Sizes——While commercial catalytic oxidizers range in capacity from about 300 to 40,000 scfm, available information indicates that most existing units have capacities in the 3,000-18,000 scfm range. The dimensions of typical catalytic oxidation units could not be determined from available information, but are estimated to range from about 3-18 ft^2 in cross-section and 10'-20' in length.

b. Configuration——Most catalytic incinerators are designed with burner and catalyst bed in a straight line. This arrangement, however, can result in high surface temperature on the face of catalyst bed due to radiant heat from the auxiliary fuel burner flame. To minimize this problem, the catalyst bed is located at least 5-10 ft downstream of the burner and baffles are placed in the mixing section to blind the catalyst to the flame, or the catalyst bed is located at right angles to the mixing chamber. The latter approach results in an "L" or "U" shaped configuration which can cause gas flow not to be uniform, a condition that can continue through the catalyst, possibly resulting in decreased oxidation performance. Although no specific data were found to confirm this effect, an in-line configuration is recommended, which will make design and construction easier.

The mixing and catalyst bed chamber should be sized to minimize the effect that large interior and exterior surface area-to-volume ratios can have on oxidizer performance. Small chamber sizes (<1 ft^2 cross-section) result in high interior and exterior surface area-to-volume ratios which can result in gas mixing characteristics and surface heat

losses not representative of full-scale units. A mixing chamber of at least 1 ft^2 in cross-section is therefore recommended for the pilot unit. Also, to assure that surface heat losses do not significantly increase burner firing rates, it is recommended that the unit be insulated to keep heat losses to less than 5% of the maximum burner firing rate.

c. Scale-Up Factors -- Based on a limited review of available information and vendor discussions, pilot catalytic oxidation systems appear to fall into two size ranges, <100 scfm and 1000-3000 scfm. Full-size system design based on small laboratory-scale (<100 scfm) tests can result in scale-up factors as high as 4000:1, whereas design based on operation of the larger capacity pilot systems will give scale-up factors only as high as 40:1. The small units are particularly useful for experimental work on reaction kinetics, compound thermal stability and identification of ideal catalyst and space velocity requirements for destruction of organics. The small systems are often electrically heated thereby eliminating "flame contact" as a factor in the preheating process. Frequently, the provisions for mixing the waste gases with the hot combustion gases are not representative of full-scale processes.

The larger pilot systems (1000-3000 scfm) are usually small size production designs which are used to obtain data for the optimum design of a much larger unit. The lower limit of a representative pilot unit size appears to be about 250 scfm, which is determined by available burner sizes, burner-chamber geometry, and heat loss factors. If a 4:1 turn-down of gas flow is desired to investigate effect of changes in space velocity, then a unit sized for 1000 scfm is recommended as the minimum for a pilot unit with provisions for operating at 250 scfm.

4. Safety Requirements

A pilot incinerator for temporary installation at several test sites must not only meet national standards and codes for fuel burning equipment but also any safety regulations or codes required by local government agencies or the host plant's safety department. While it is im-

practical to try to identify all possible safety requirements, the majority can be satisfied by following the codes, standards and recommended practices published by the National Fire Protection Association (NFPA). Official approval of system design by NFPA will satisfy most local codes. It should be anticipated, however, that a formal review and approval may be required by the owner's safety department and/or the industrial insurance underwriter for each plant site. Detailed piping and instrument drawings must be prepared and maintained current for safety review purposes. Inspection of the installed system by owner and operator representatives prior to start-up should be mandatory.

Due to the cyclical nature of many process operations or to process upsets, the concentration of VOC in waste gas streams can vary from dilute to very concentrated; as a result concentrations may be in the combustible range for a period of time. For this reason and because pilot unit operators may not be familiar with process variables, it is recommended that the concentration of combustible gases in the waste stream be continuously monitored with the capability for automatic shut-off of waste gas flow and purging with ambient air.

Some potential test sites may be in plant areas where explosion-proof equipment construction is required. A recommended procedure is to duct the gases to a safe area where standard materials and procedures can be applied. The operation of a pilot thermal oxidizer in hazardous areas is not recommended because the special equipment and procedures required would significantly increase equipment costs, testing program costs and the risk of worker injury and property loss. Special sampling equipment and analytical procedures would also be required in such an environment. Explosion-proof construction is not considered necessary or advisable for the pilot unit.

5. Process Condition Measurements

Considerably more data on process temperatures, gas flows, pressure drops, and gas compositions should be collected from a pilot unit than

is normally provided for in a full-scale unit. The data are important for assessing the effects changes in critical design parameters have on system performance. The collected data should not only permit definition of effective process conditions but also calculation of confirmatory heat and material balances and assessment of performance of individual equipment components.

The process measurements recommended for the various gas streams in the pilot unit are identified in Table IV-1. The table is intended only to indicate that provisions for taking the measurements be included in the design of the pilot unit. For example, a temperature indicating recorder-controller is recommended for final preheat temperature while sampling ports are all that is necessary for the flow rate and gas composition measurements. The actual measurements will be part of an associated sampling and analytical program. The decisions as to which process conditions should be automatically indicated, controlled and recorded, indicated only, or obtained by utilizing portable instruments at sample ports are considered part of the detail design and beyond the scope of this project.

The sampling ports for the waste VOC streams and the stack gases should be sized to permit sampling for particulates by EPA method 5. Sampling ports for measurement of gas velocity and determination of flow rates should be designed for use of EPA method 2. Sampling ports for collection of hot gas samples should be sized for the special probes required to withstand the high temperatures.

6. Transportability

The pilot system should be of single unit or modular component construction that can be transported by trailer or shipped by commercial truck carrier. The system unit or its components should be steel frame skid-mounted for easy handling at test sites. It is assumed that the unit will be installed on and operated from a flat-bed or low-boy trailer. Construction of a modular unit which can be shipped by commercial carrier, offloaded by fork truck or overhead crane and operated at ground or roof level can also be considered during detail design.

Table IV-1. Recommended Process Measurements for a Pilot Catalytic Oxidation System

	Temperature	Pressure	Flow Rate	Gas Composition
Waste VOC stream				
Source gas	X		X	X
Heat exchanger inlet	X	X		
Burner section inlet	X	X		X[a]
Preheated gas stream				
Burner section outlet	X	X		X[a]
Catalyst bed inlet	X			X[a]
Heat exchanger inlet	X	X		
Heat exchanger outlet (stack)	X	X	X	X
Auxiliary fuel				
Natural gas			X	

[a]Necessary only for specific situations.

The maximum weight of any single component should not exceed 6000 lb to remain within the load-carrying capacity of a large fork truck. For shipping convenience, the maximum dimensions of the unit or any component should be less than 8 ft wide by 10 to 15 ft long by 6 to 8 ft high. Although there is no limit on the size of an assembled modular pilot system, it should be kept as small as possible to minimize cost and handling problems. Overall road height for trailer and pilot unit must not exceed 13 ft 6 in. Normal over-the-road width of 8'0" is desirable, but transportation of 10 ft 0 in. wide loads is possible with special permits required in some states. An overall weight limit of 18,000 lb per axle should be acceptable in all states.

The individual components and the assembly must be designed to withstand the vibrations and shock of highway transport and the stresses of loading and off-loading.

7. Assembly and Operating Considerations

The pilot system should be designed for easy assembly and connection to local utility services. It is assumed that the unit will be assembled under the direction of a pilot system operator with assistance as required from local tradesmen such as millwrights, electricians, and pipefitters.

It is anticipated that the unit will be used at any one test site for periods ranging from 1 week up to 3 months. While provision for continuous operation for longer periods to gather data on catalyst life may be necessary, each data gathering session is expected to be completed within 8 hours.

The unit should be designed for manual start-up and shut-down and automatic operation by a single experienced operator. Waste gas, dilution air, flows, and recuperative preheat temperature will be set manually. Only the final preheat temperature will be automatically controlled. Instruments and controls will be provided for automatic shutdown in case of preheat or stack gas overtemperature waste gas concentrations >25% LEL at the fan inlet. It is assumed that the overall operation of the pilot system will be under the direction of a test program manager.

The sampling and analytical program for determining system performance is beyond the scope of this project. It is anticipated however that this program will require a minimum of two people who will operate out of a mobile laboratory specially equipped for the purpose.

E. PRELIMINARY PROCESS DESIGN

1. Process Description

A block process flow diagram for the pilot catalytic oxidation system is shown on Fig. IV-1. The diagram illustrates the major system components that will be required to meet the full range of capabilities previously described in the design bases.

As shown on the process flow diagram, 250 to 1000 scfm of waste gas at 100°F is drawn from a VOC source, with the flow rate being determined by a manually set volume control damper. If the concentration of organic in the waste gas is less than 25% LEL and contains sufficient oxygen for complete combustion, the waste gas is forwarded by fan through a high gas velocity section of duct (flame flashback preventers) to the recuperative shell and tube heat exchanger where it is heated to a maximum of 700°F by indirect exchange with the hot (1200°F) flue gases.

If the concentration of organics in the waste gas exceeds 25% LEL, or if the gas is oxygen deficient, then ambient air can be drawn in to dilute the organics or increase the oxygen content with the amount being determined by manually setting the volume control damper. The waste gas and ambient air mixture is then forwarded to the heat exchanger as described above. The volumetric flow rate of the mixture should not exceed 1000 scfm.

The waste gas volume control damper should automatically close and the dilution air damper automatically open upon shut-down of the catalytic oxidation system for any reason. This action should also occur if the concentration of the VOC reaches the combustible range at the inlet to the main blower.

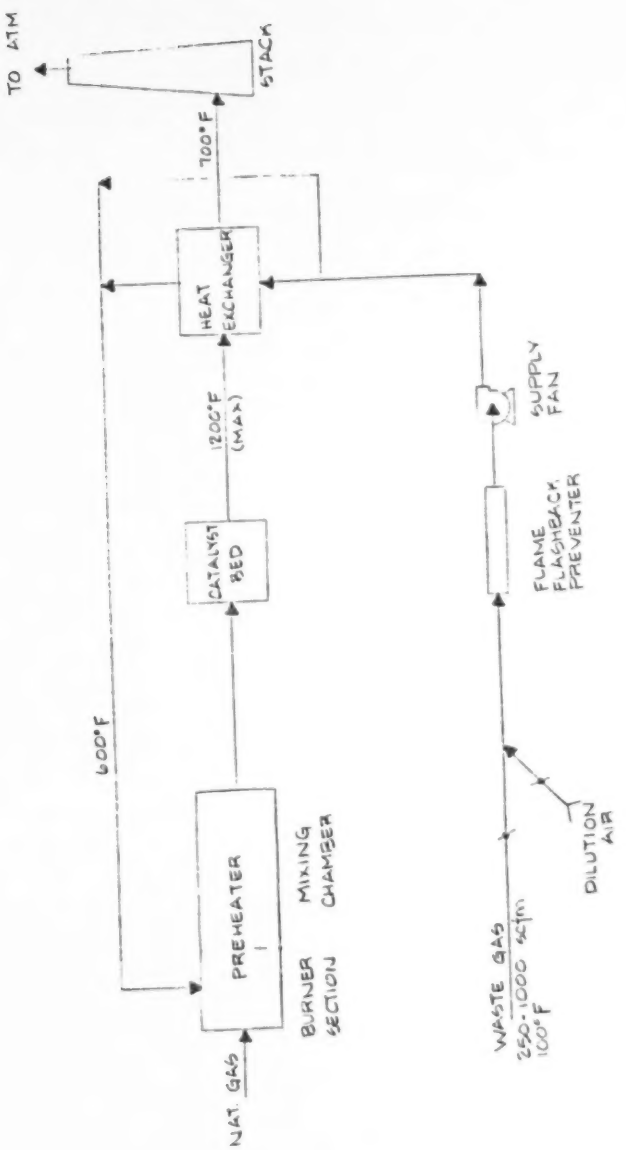


Fig. IV-1. Preliminary Process Flow Diagram for Pilot VOC Catalytic Oxidation Unit

For waste VOC streams at temperatures >100°F, it may be necessary to reduce the amount of heat recovered from the flue gases. The preheat temperature can be controlled by by-passing a portion of the waste gas around the heat exchanger as shown.

The heated waste gas from the recuperative heat exchanger then flows to the preheat section and through the auxiliary fuel burner where, if required, it can be further heated to the final preheat temperature by mixing with the hot gases from the combustion of natural gas. The mixing of the waste gases continues as the gases flow through the mixing chamber. The temperature of the gases in the mixing chamber are measured by thermocouple and automatically controlled by adjusting the flow of natural gas through the supply valve.

The preheated gases then pass through the catalyst bed where the VOCs are oxidized to CO_2 and H_2O with the released heat raising the gas stream temperature to a maximum of 1200°F (normal range of 800-1100°F).

The combustion product gases then pass through the recuperative heat exchanger where they are cooled from 1200°F to 700°F and then through the stack to the atmosphere.

2. Equipment List

The major components of the pilot catalytic oxidizer are listed below. When available, estimates of capacity, size, weight are also listed to briefly describe the equipment.

a. Inlet Duct Section——Waste gas volume control damper (0——1000 scfm), dilution air volume control damper (0——500 scfm), venturi (flame flashback preventer). (Insulation is not required for gas design temperature of 100°F. If gas temperatures >140°F are encountered, insulation or heat shields can be provided at that time for personnel protection.) Weight is estimated at <200 lb.

b. Main Supply Blower——1000 scfm capacity at estimated 12 to 16 in. W.C. pressure and at maximum operating temperature of 400°F. Belt driven with adjustable sheaves and shaft seals. Motor horsepower is roughly estimated at 3 to 5 HP range. Weight is estimated at ~150 lb.

c. Recuperative Heat Exchanger——Shell and tube type; ~0.6 MM Btu/hr capacity; waste gases tube side (100 to 600°F) and flue gases shell side (1200 to 700°F). Stainless steel tube and mild steel shell construction required. Include by-pass ductwork and two flow control dampers. Components insulated to maintain surface temperatures <140°F. Weight is estimated in 500 to 800 lb range.

d. Preheating Section——Consists of inlet plenum, natural gas burner, and waste gas/auxiliary fuel combustion gas mixing section. Burner assembly to be of distributed type with full waste gas flow through the burner or with partial waste gas by-pass of burner and subsequent mixing at the flame front. Maximum burner capacity estimated at ~0.6 MM Btu/hr with a turndown capability of at least 4:1 and preferably 10:1.

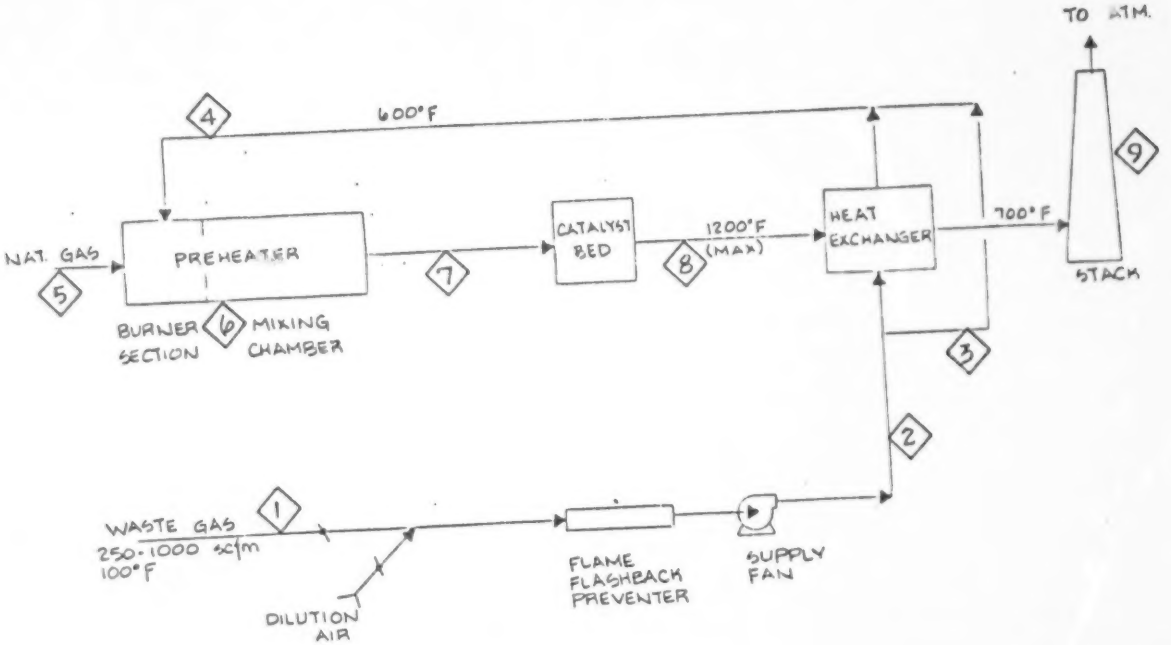
The mixing section will be a mild steel chamber lined with insulation inside and possibly covered outside to minimize surface heat losses (<5% maximum burner firing rate) and to protect personnel from hot surfaces. Removable baffles will be included inside the mixing chamber.

e. Catalyst Bed——Removable assembly capable of holding catalyst material approximately 1 ft^2 in cross-section and from 8 in. up to 24 in. depth. The catalyst material will be selected to meet specific application. Catalyst density is expected to range from 40-50 lb/ft^3. The weight of this section is estimated at 200 to 400 lbs.

f. Stack——Mild steel duct of approximately 1 ft diameter. Minimum length estimated at 15 ft; actual length to be determined by gas dispersion or site requirements. Design must include insulation or heat shields for personnel protection. Stack must be detachable for transport.

3. Instruments and Controls

The locations for process measurements and sampling points are shown on Fig. IV-2. The major components are listed below.



	1	2	3	4	5	6	7	8	9
TEMPERATURE	X	X		X		X	X	X	X
PRESSURE	X	X		X			X	X	X
FLOW RATE		X	X		X				X
SAMPLE PORTS	X	X				X	X	X	X

Fig. IV-2. Recommended Locations for Measurement of Process Conditions - Pilot VOC Catalytic Oxidation Unit

a. Process Control Instruments——Flame safeguard system; combustion temperature; high temperature limits on gases in the preheat chamber and at the inlet to heat exchanger; high and low natural gas pressure; low waste gas pressure (flow) at inlet to burner section. Combustion gas analyzer with automatic shut-off of waste gas flow and opening of dilution air valve upon oxidizer shutdown.

b. Process Monitoring Instruments——Temperature: waste gas inlet, heat exchanger inlet, burner section outlet, catalyst bed inlet and outlet, and stack. Pressure: main fan outlet. Other measurements obtained manually with portable instrument at sample ports. Temperature recording requirements to be defined during detail design.

4. General Construction Guidelines

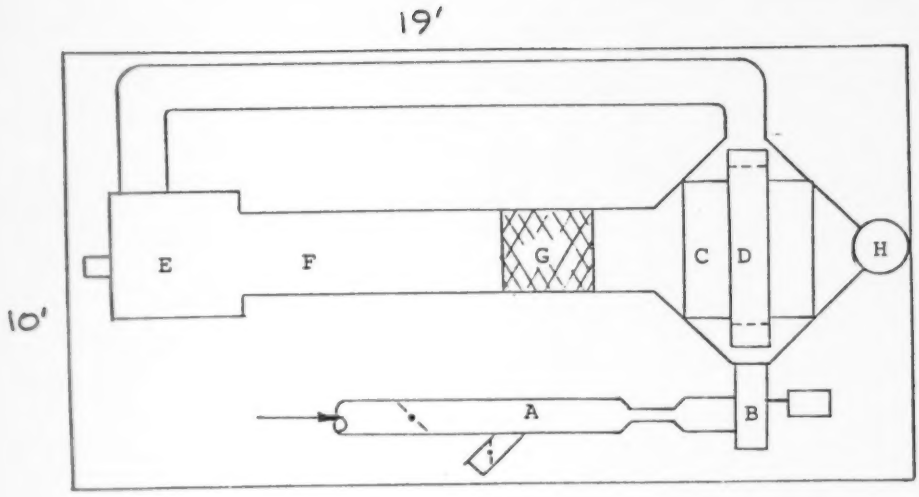
General requirements for design for transportation were previously discussed in paragraph D.6. To meet the stresses and vibration of handling and transportation, the pilot system components will be attached to heavy duty steel frame of welded construction wherever feasible. Screwed or bolted construction will be designed to resist loosening due to vibration. Shock absorbent mounting may be necessary for some components. Components especially sensitive to damage such as recorders, controllers, combustible gas analyzers, should be demountable for separate shipping in shock absorbent packaging.

A conceptual arrangement of the pilot unit is shown in Fig. IV-3. This arrangement was developed in order to estimate unit sizes. Based on this preliminary concept, the size of the unit is roughly estimated to be 10 ft wide by 19 ft long.

5. Estimated Requirements for Operation

It is assumed that all utilities will be furnished to the pilot unit by the test site owner. Very preliminary estimates of utility requirements are summarized below.

a. Electrical——Control panels and service outlets: 120 V/1ϕ/60 Hz, 2-4 kw. Fan motors: 220/440/3ϕ/60 Hz, 4-8 Hp.



A - Inlet
B - Supply blower
C - Heat exchanger
D - Bypass duct
E - Burner Section
F - Mixing chamber
G - Catalyst bed
H - Stack

Fig. IV-3. Conceptional Arrangement
Pilot VOC Catalytic Oxidation System

b. Auxiliary Fuel—Natural gas: 600 CFH maximum, 150 CFH estimated average use.

Assembly and connection of the pilot unit should be accomplished by the agency or contractor responsible for conducting the test program. The system should be designed for start-up in about two days elapsed time after being set at the test site.

F. COMMERCIALLY AVAILABLE EQUIPMENT

1. Pilot Unit Size

Almost any type of system is available from manufacturers with sizes ranging from ~10 scfm laboratory-scale units to about 3000 scfm full-scale operating units. Typical of the industry, almost every unit is designed for a specific process requirement.

Based on other ongoing studies of IT Enviroscience and on brief discussions with vendors, it is believed very important that a pilot unit be of a size, physical configuration and components that are representative of full-scale units. Scale-up factors of <40:1 will be considerably more reliable than factors approaching several 1000:1.

For these reasons, a 1000 scfm capacity unit was selected as the minimum for acquiring scale-up data.

2. Cost Estimate

A catalytic oxidation and heat recovery system for pilot test purposes will be very similar to a standard design system with the exception that it will be capable of a wider range of operating conditions and have special provisions for monitoring each process operation. The budget-type estimate for a pilot catalytic oxidation unit is as follows:

Catalytic oxidizer	$37,000
Heat exchanger	33,000
	$70,000

The catalytic oxidizer includes burner, combustion and mixing chamber, catalyst, fan, inlet duct with waste gas bypass and dilution air inlet and stack. The heat exchanger is based on ~0.6 MM Btuh capacity and U=4 Btu/hr/ft^2/°F and includes a waste gas bypass. The cost estimate is based primarily on cost curves previously included in another EPA document.(9)

3. Availability

Only three manufacturers were identified as potential suppliers of a pilot catalytic oxidizer, listed as follows:

E. I. duPont de Nemours & Company, Inc.
Wilmington, DE 19898

Engelhard Minerals & Chemicals Corporation
Engelhard Industries Division
2655 U.S. Route 22
Union, NJ 07083

Met-Pro Corporation (formerly Oxy-Catalyst, Inc.)
Systems Division
160 Cassell Road
P. O. Box 144
Harleysville, PA 19438

Other manufacturers may be capable of supplying a pilot unit, but they could not be identified within the limits of this preliminary design study.

V. CONDENSATION PILOT PLANT

A. GENERAL

The purpose of a condensation pilot unit is to obtain data for scale-up to a full size unit, if such data are not already available or cannot be obtained by other more cost-effective methods.

Condensation is an operation in which one or more volatile components of a vapor mixture are separated from the remaining vapor by being changed to the liquid phase through extraction of the heat of condensation. In a two-component vapor stream, where one of the components is considered to be noncondensible (e.g., air), condensation occurs when the partial pressure of the condensible component (e.g., VOC) is reduced to equal the component's vapor pressure. To achieve this condition the system pressure may be increased at a given temperature or the temperature of the vapors may be reduced at constant pressure.

This section briefly covers the status of condensation technology and presents the conclusions and recommendations.

B. STATUS OF CONDENSATION TECHNOLOGY (12)

Condensation is used extensively in the chemical process industry. There are many vendors who manufacture condensers and some have a stock of ready-made condensers in a few popular sizes. Condensers are usually manufactured for specific applications and often to preengineered general purpose designs with modular dimensions.

Although condenser design is a complex task, there are many technical reference books and articles covering the subject. Many vendors have a staff of engineers who specialize in design of condensation equipment for the purchaser's requirements. The data required to design a condenser includes temperature, composition and flow of the waste gas stream and the physical properties of each component, usually available from the literature or from the owner of the process that has the emission. A thorough sampling program should be employed to characterize

the waste gas stream. Where there are data gaps in physical property data, a program to measure the specific property data needed is more cost effective than installing a condensation pilot unit.

Condensation as an emission control method is often used with auxiliary air pollution control equipment.(13) For example, condensers can be located before (upstream of) absorbers, incinerators, or carbon beds to reduce the VOC load on the more expensive control device, thereby reducing the size and cost of the other control device. The condenser can also remove vapor components that might adversely affect the operation of other equipment or cause corrosion problems or can be used to simply recover valuable material that would otherwise be destroyed. When condensers are used alone, as in gasoline vapor control from bulk terminals, refrigeration is often employed to obtain the low temperatures necessary for acceptable VOC removal efficiencies.

The VOC removal efficiency of a condenser system is determined by the amount of reduction in the VOC partial pressure in the gas stream as it passes through the condenser. This is accomplished by reducing the temperature of the gas stream and condensing out some of the VOC. Any component of any vapor mixture can be recovered (condensed) if brought to equilibrium at a low enough temperature. The temperature necessary to obtain a particular VOC vapor concentration or removal efficiency is dependent on the vapor pressure of the components. When a two-component vapor mixture, in which one of the components is considered to be noncondensible, is cooled, condensation will begin when the temperature reached is such that the vapor pressure of the volatile component is equal to its partial pressure. This fact limits the cost-effective use of condensation for control of VOC to a small group of compounds that have appropriate vapor pressures and high values. Another limiting factor is the concentration of VOC in the emission, i.e., dilute VOC streams can often be controlled in a more cost-effective manner using control techniques other than condensation.(14)

C. CONCLUSIONS

There is usually no need for data from a condensation pilot unit when designing a full-scale condenser. Data from literature and other sources and the characterization of the waste stream to be controlled are often adequate for design.

D. RECOMMENDATIONS

It is recommended that design and construction of a pilot condensation unit not be included in EPA's plans at this time. Existing engineering data should be used for design of condensers for the few applications where they are appropriate emission control devices. As an alternative, a special condenser could be provided as part of the carbon adsorption unit and used separately as a condensation pilot unit if one is needed.

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*Usually, when a reference is located at the end of a paragraph, it refers to the entire paragraph. If another reference relates to certain portions of that paragraph, that reference number is indicated on the material involved. When the reference appears on a heading, it refers to all the text covered by that heading.